The Future of RHIC: An eRHIC Physics Overview

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RHIC & AGS Users' Meeting

Pressing Questions in QCD

- How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?
  - How are these quark and gluon distributions correlated with overall nucleon properties, such as spin direction?
  - What is the role of the orbital motion of sea quarks and gluons in building the nucleon spin?

- Where does the saturation of gluon densities set in?
  - Is there a simple boundary that separates this region from that of more dilute quark-gluon matter?
  - If so, how do the distributions of quarks and gluons change as one crosses the boundary?
  - Does this saturation produce matter of universal properties in the nucleon and all nuclei viewed at nearly the speed of light?

- How does the nuclear environment affect the distribution of quarks and gluons and their interactions in nuclei?
  - How does the transverse spatial distribution of gluons compare to that in the nucleon?
  - How does nuclear matter respond to a fast moving color charge passing through it?
  - Is this response different for light and heavy quarks?

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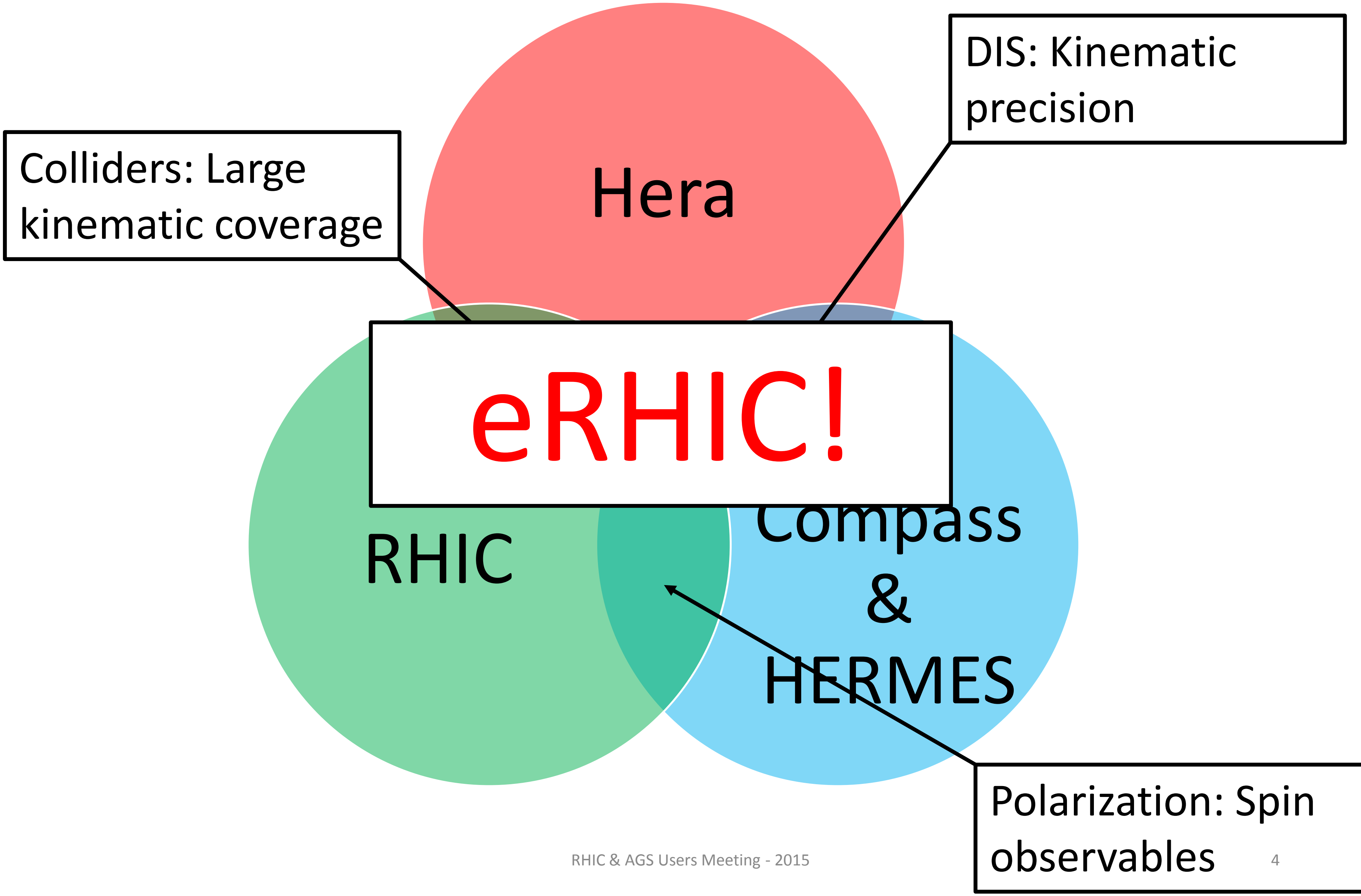
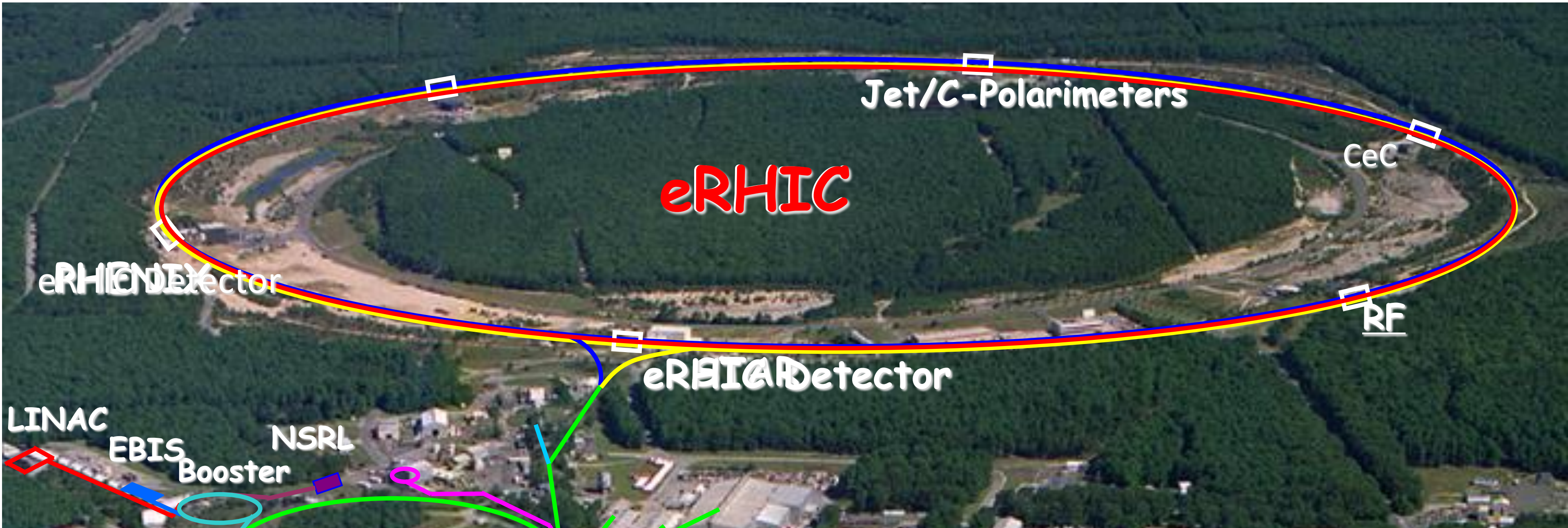
eRHIC: Polarized ep Collider



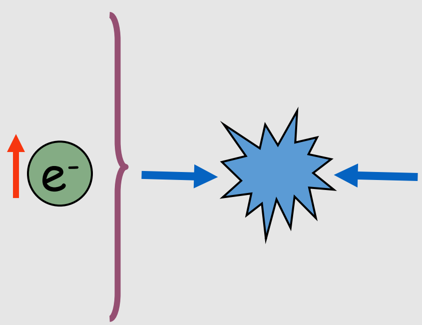
From RHIC to eRHIC



Electron accelerator

to be build

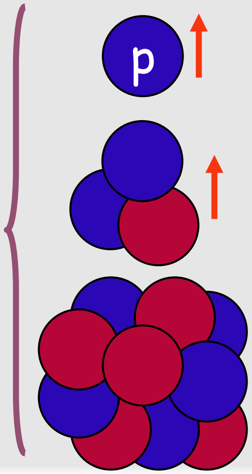
polarized leptons
15 & 21.2 GeV
and lower
E_e >1.6 GeV



goal: 80% e^- polarization

RHIC

Existing = $2B



70% Polarized protons
25-250 GeV

Polarized light ions He^3
17-166 GeV/u

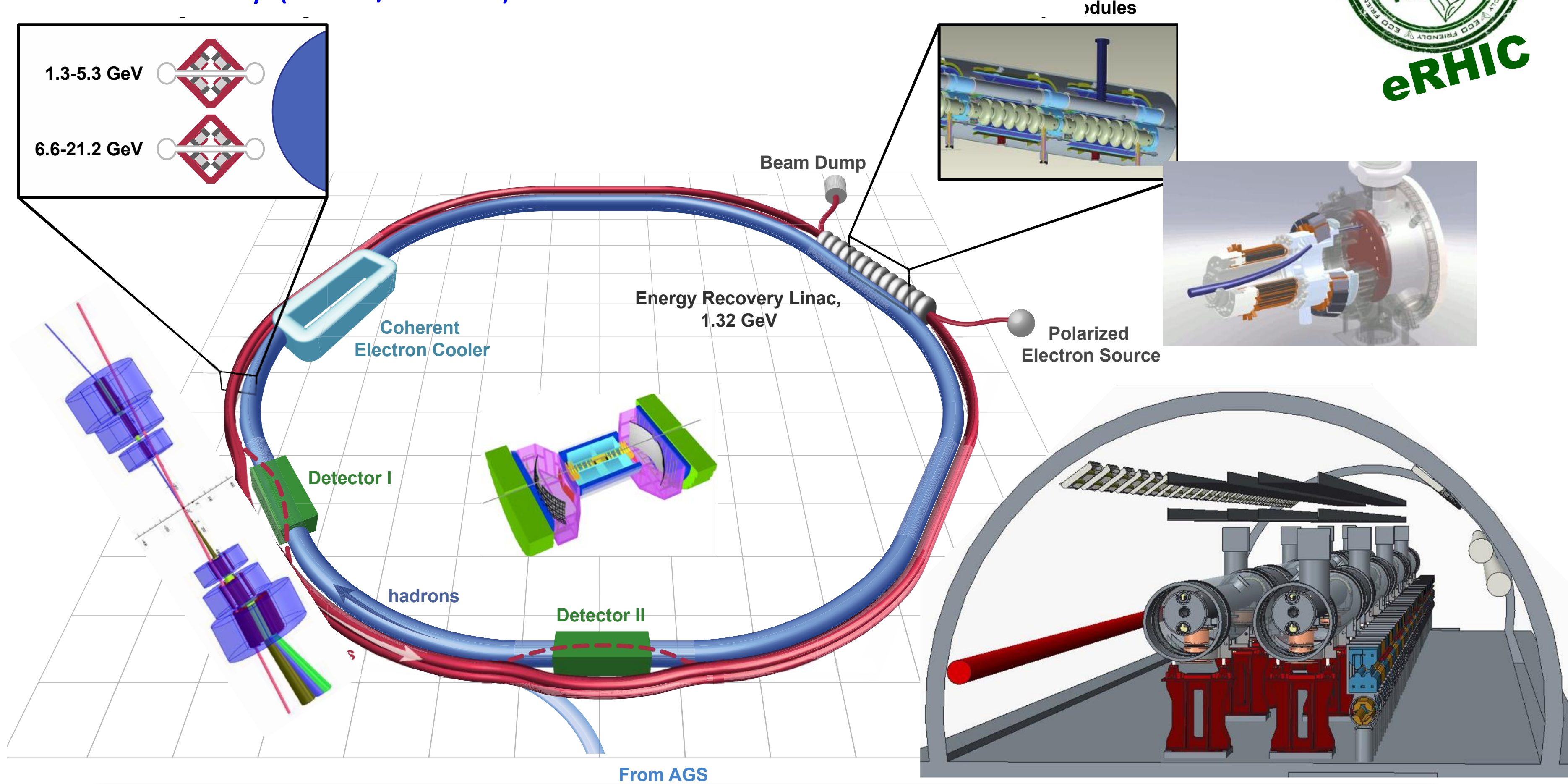
Light ions (d,Si,Cu)
Heavy ions (Au,Pb,U)
10-100 GeV/u

eRHIC Design

eRHIC:

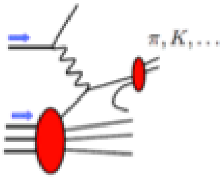
Energy recovery linac + fixed-field alternating-gradient ring design

Record luminosity (>10^{33}/cm^{-2}s^{-1}) 100 – 1000 x HERA



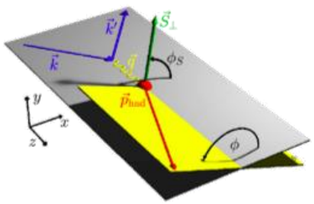
When completed, eRHIC will be the most advanced and energy efficient accelerator in the world

What is Needed



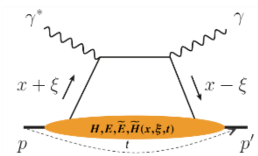
Inclusive and semi-inclusive DIS

Longitudinal motion of spinning quarks and gluons



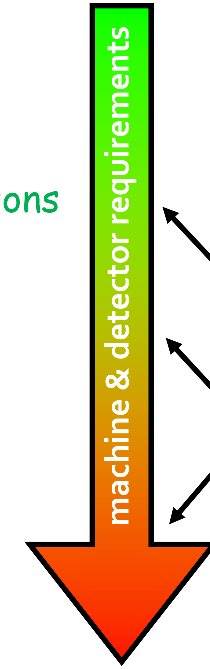
Azimuthal asymmetries in DIS

Adds their transverse momentum dependence



Exclusive processes

Adds their transverse position

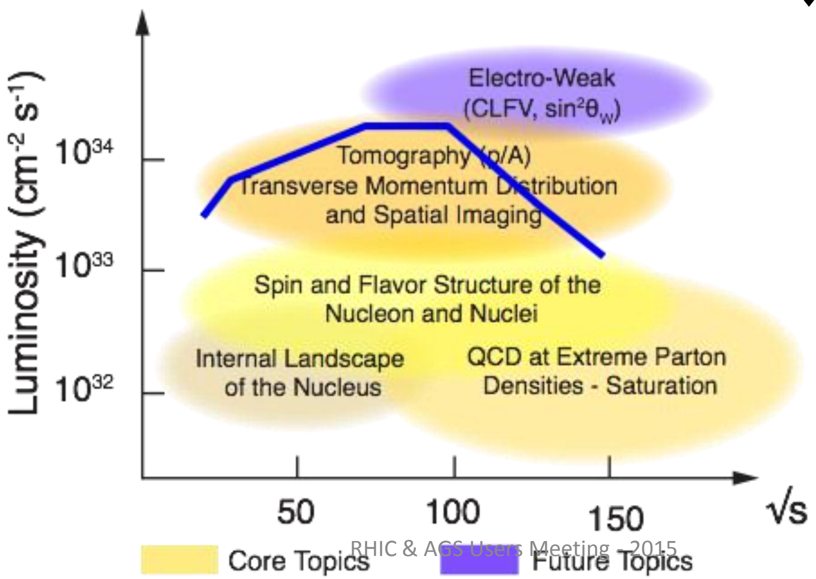


All need $\sqrt{s_{ep}} > 50$ GeV to access $x < 10^{-3}$ where sea quarks and gluons dominate

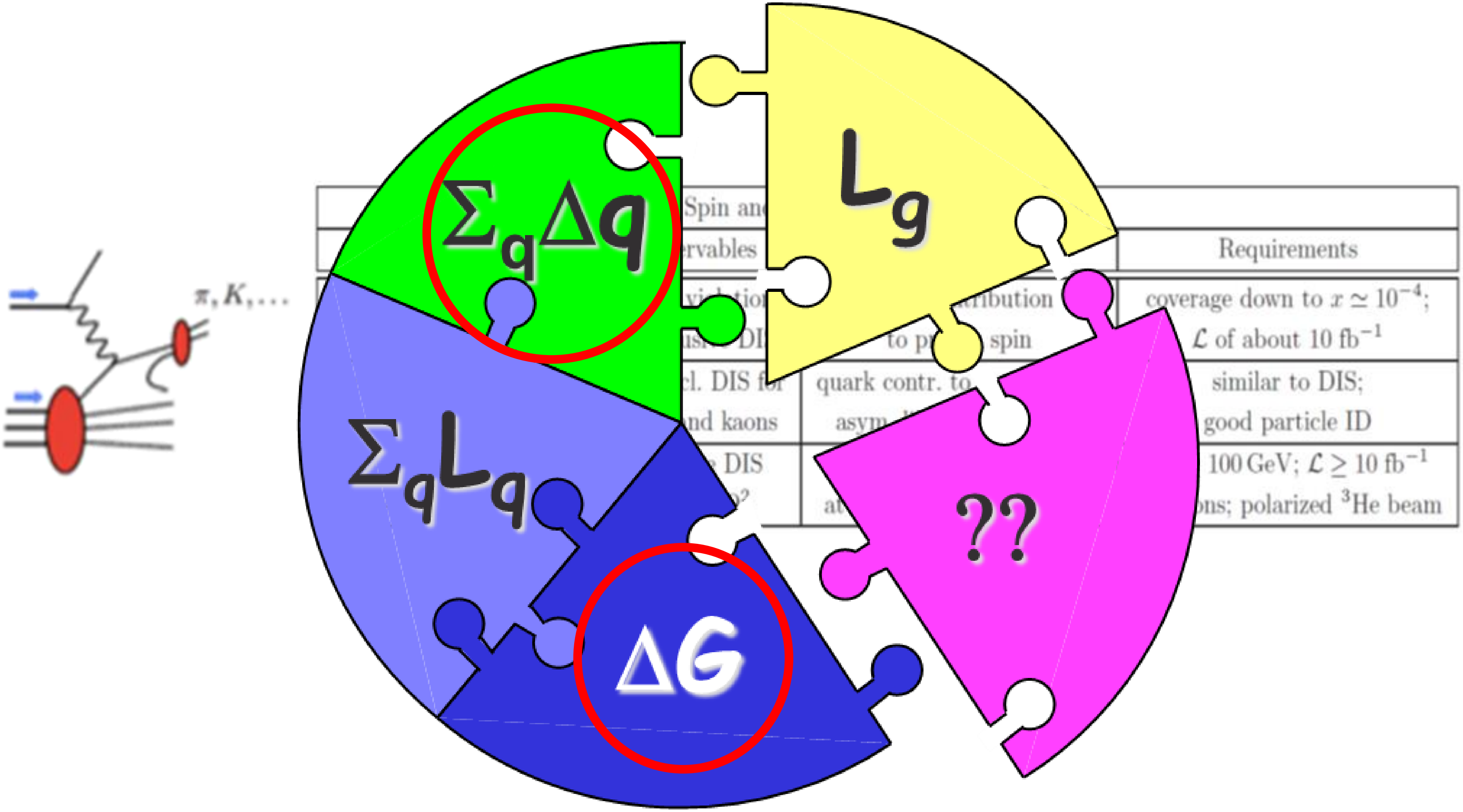
$L \simeq 10\ fb^{-1}$

$L \simeq 10 - 100\ fb^{-1}$

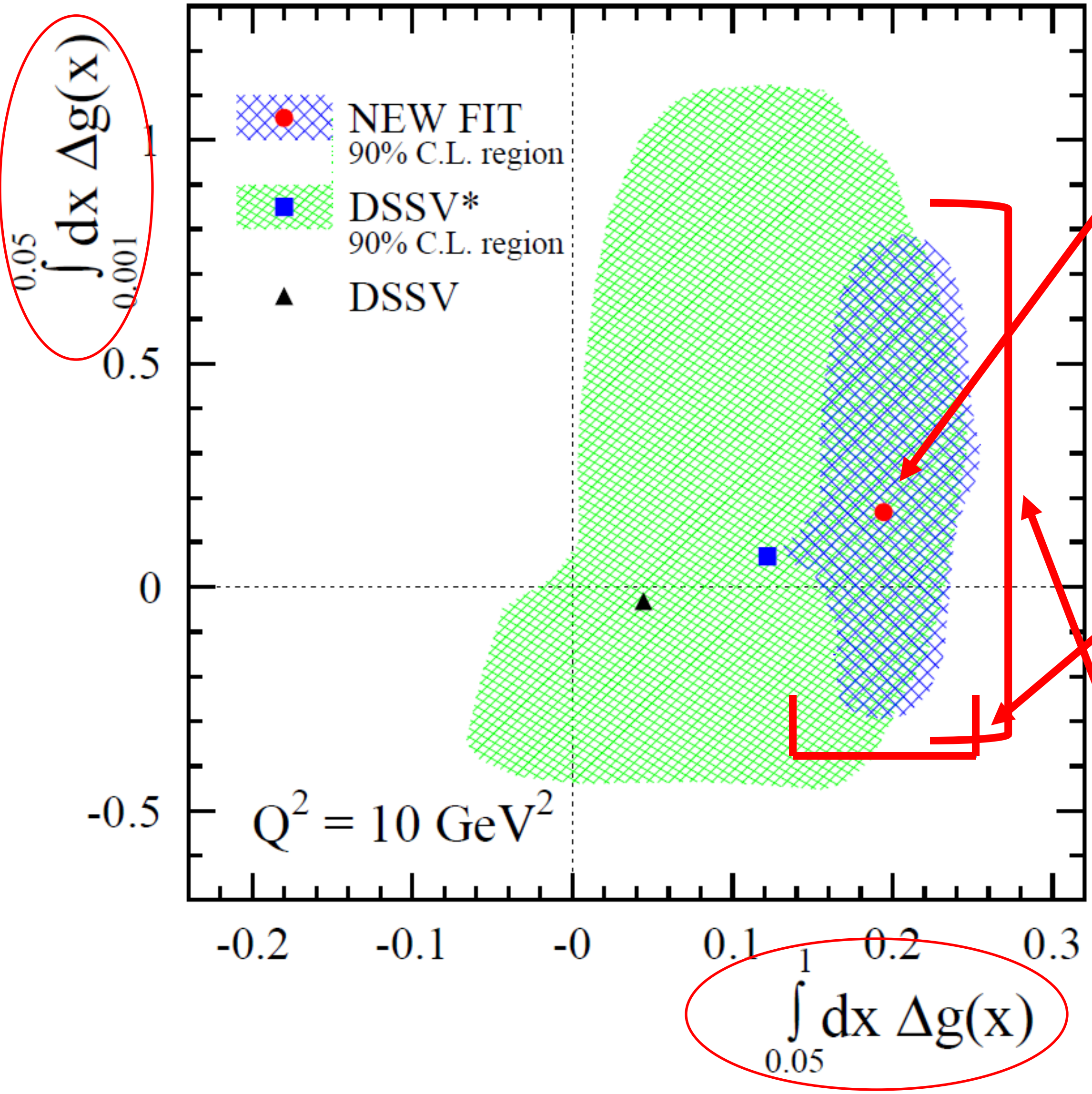
- multi-dimensional binning
  $\rightarrow$ x, Q^2, z, p_T (or t), Θ
- to reach $p_T > 1$ GeV
- to reach $|t| > 1\ GeV^2$



Longitudinal Spin Structure



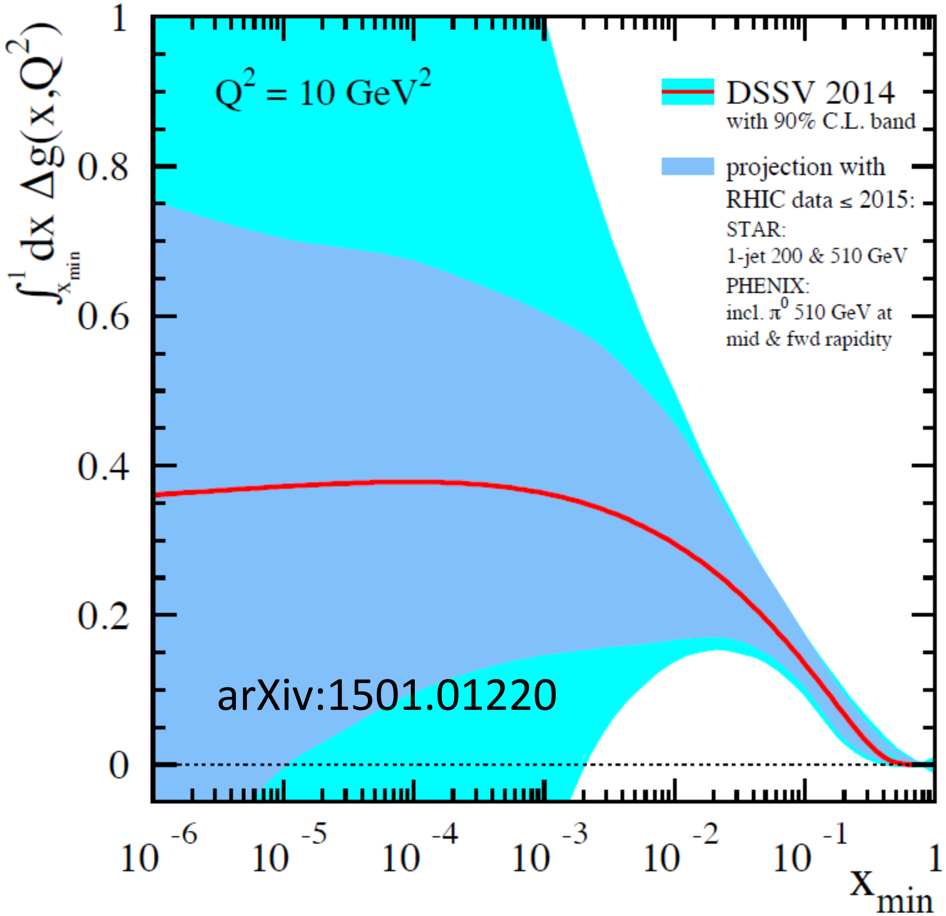
ΔG: Where Are We Now?



Phys. Rev. Lett. 113, 012001

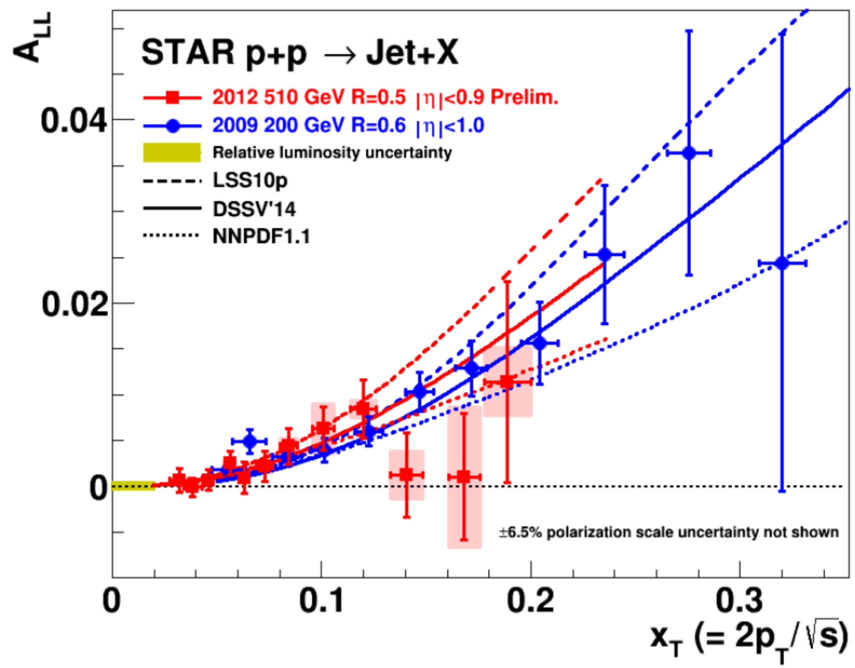
- Integral of Δg(x) in range 0.05 < x < 1.0 increases from roughly 0.05 to $0.20^{+0.06}_{-0.07}$. First indication of non-zero gluon polarization!
- Uncertainty shrinks substantially from DSSV* to new DSSV fit
- Uncertainty on integral over low x region is still sizable

ΔG: Where We Will Be Soon



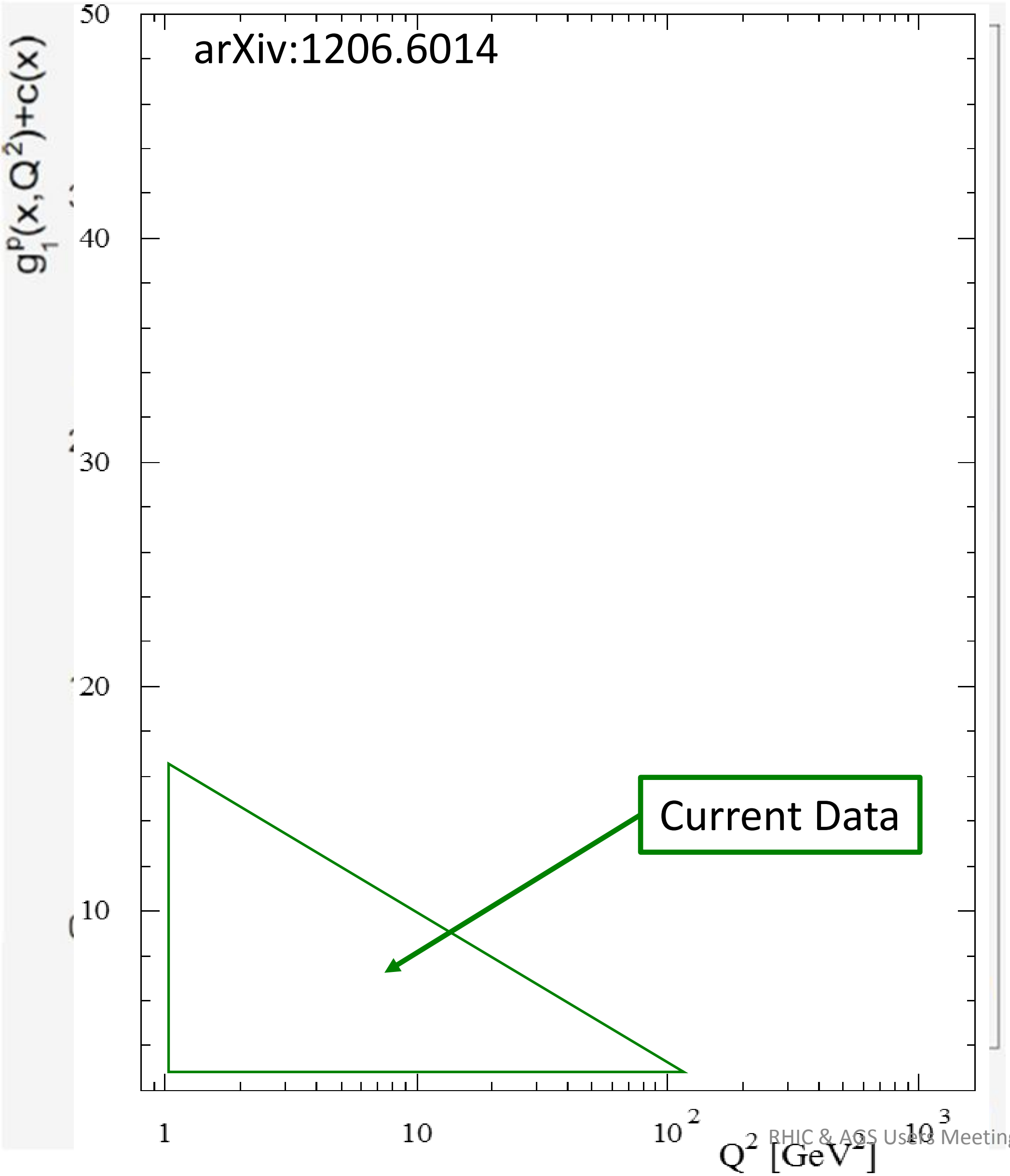
Integral of $\Delta g(x,Q^2)$ from x_{min} to 1 as a function of x_{min}

- 200 GeV: $x_{min} > 10^{-2}$
- 500 GeV + Forward Rapidity: $x_{min} > 10^{-3}$



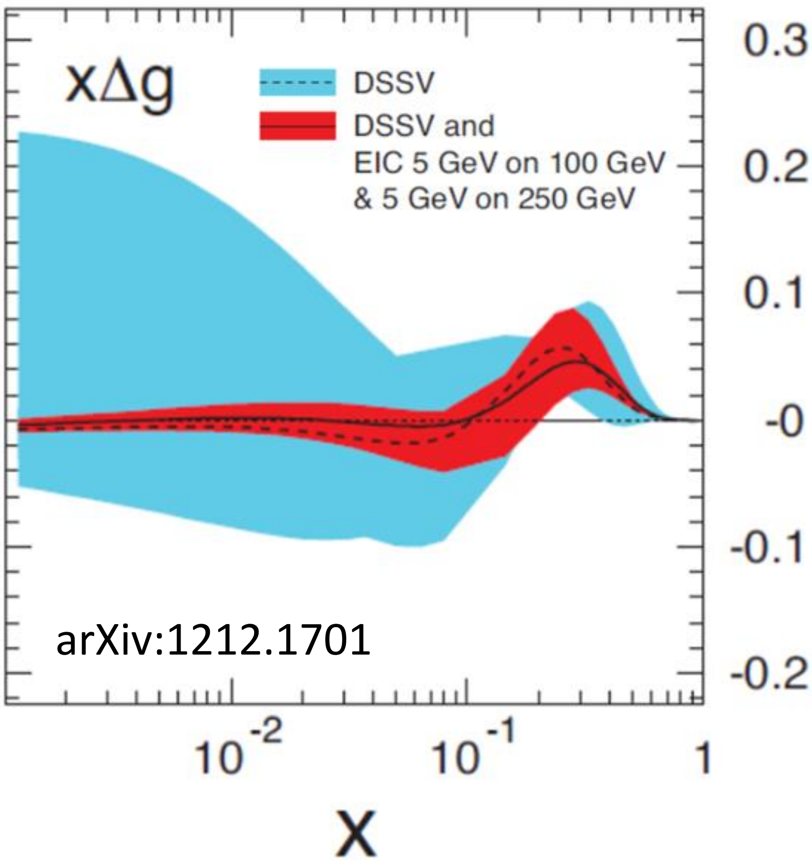
- High statistics data sets from 2012 and 2013 are being analyzed
- 200 GeV longitudinal run recently concluded
- Expected effect of data sets taken after 2009 on uncertainty of Δg running integral shown

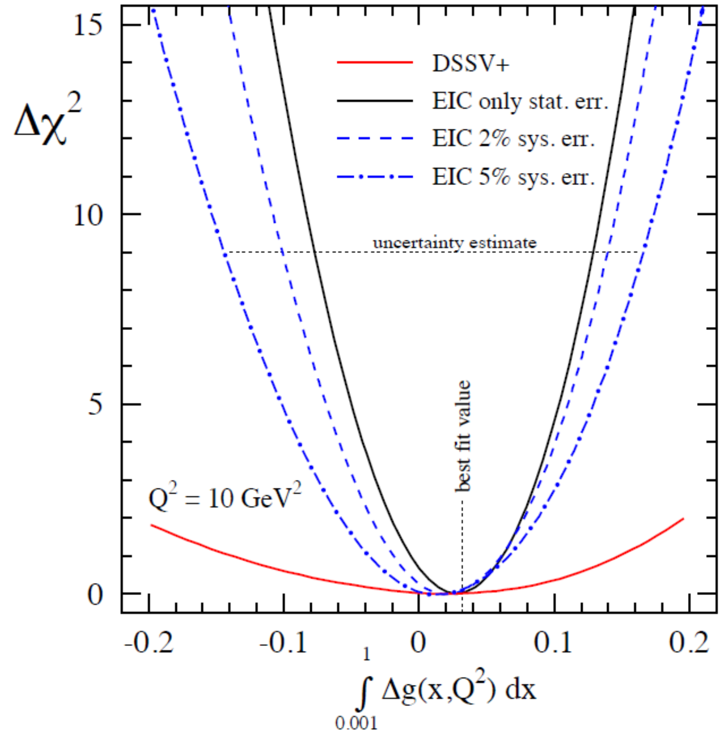
ΔG: Where We Are Going (eRHIC)



- Several observables are sensitive to ΔG in DIS but golden measurement at an eRHIC would be scaling violation of $g_1(x,Q^2)$
- Current DIS constraints on ΔG hampered by limited x & Q^2 coverage
- eRHIC would greatly expand kinematic reach and precision of $g_1(x,Q^2)$ measurements!

eRHIC: Impact on ΔG



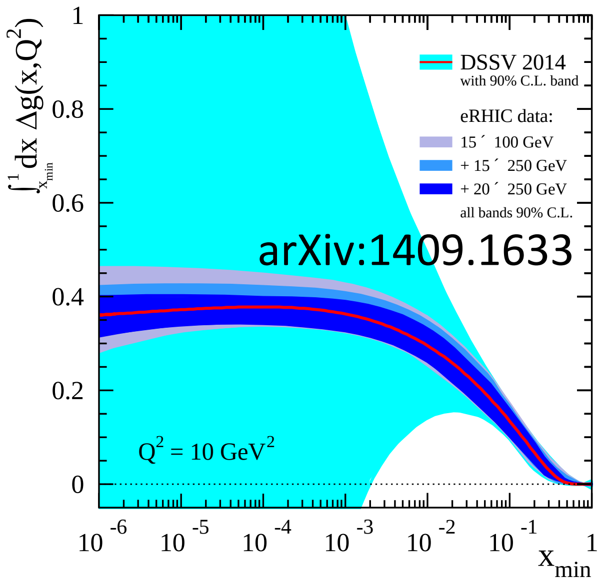


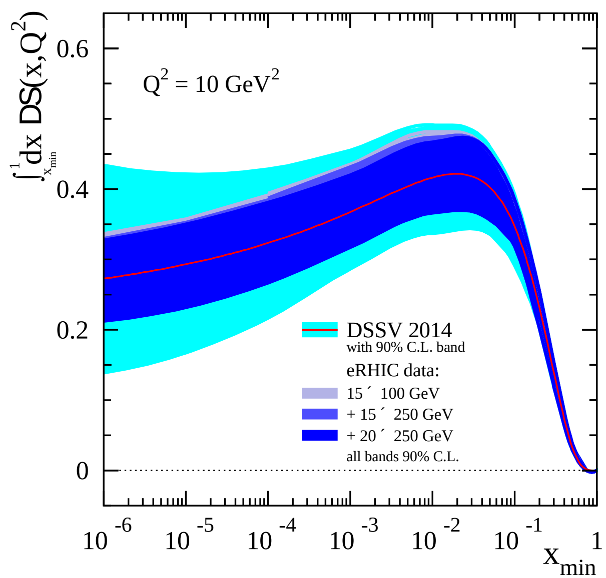
- eRHIC will have the ability to vastly reduce the uncertainty on ΔG, especially at low x where constraints from data are virtually non-existent

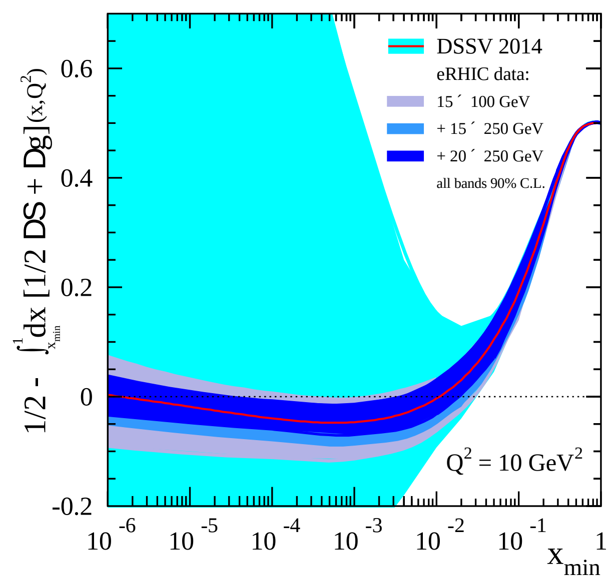
- The excellent statistical precision achievable with an eRHIC means control of systematics will be critical

- Above plot shows how the constraint on ΔG is affected by systematic uncertainty

eRHIC: Solving the Spin Puzzle







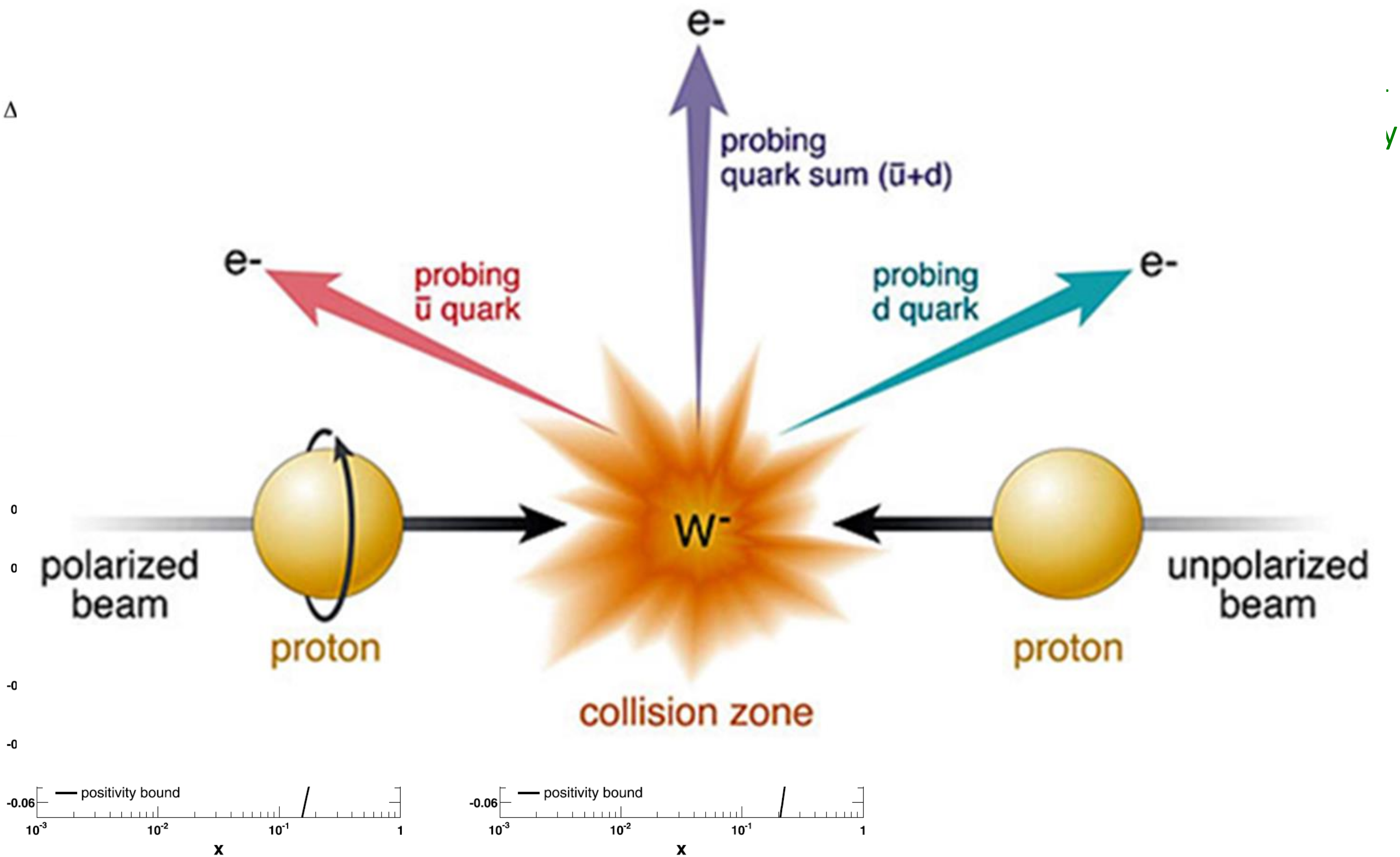
1/2 - Gluon - Quarks = orbital angular momentum

- Above plot shows the running integral of $\Delta g(x,Q^2)$ from x_{min} to 1 as a function of x_{min}
- Large reduction in uncertainty on ΔG from eRHIC can be seen

- eRHIC will also reduce the uncertainty on the quark contribution to the proton spin
- No assumptions about hyperon beta decay in eRHIC uncertainty

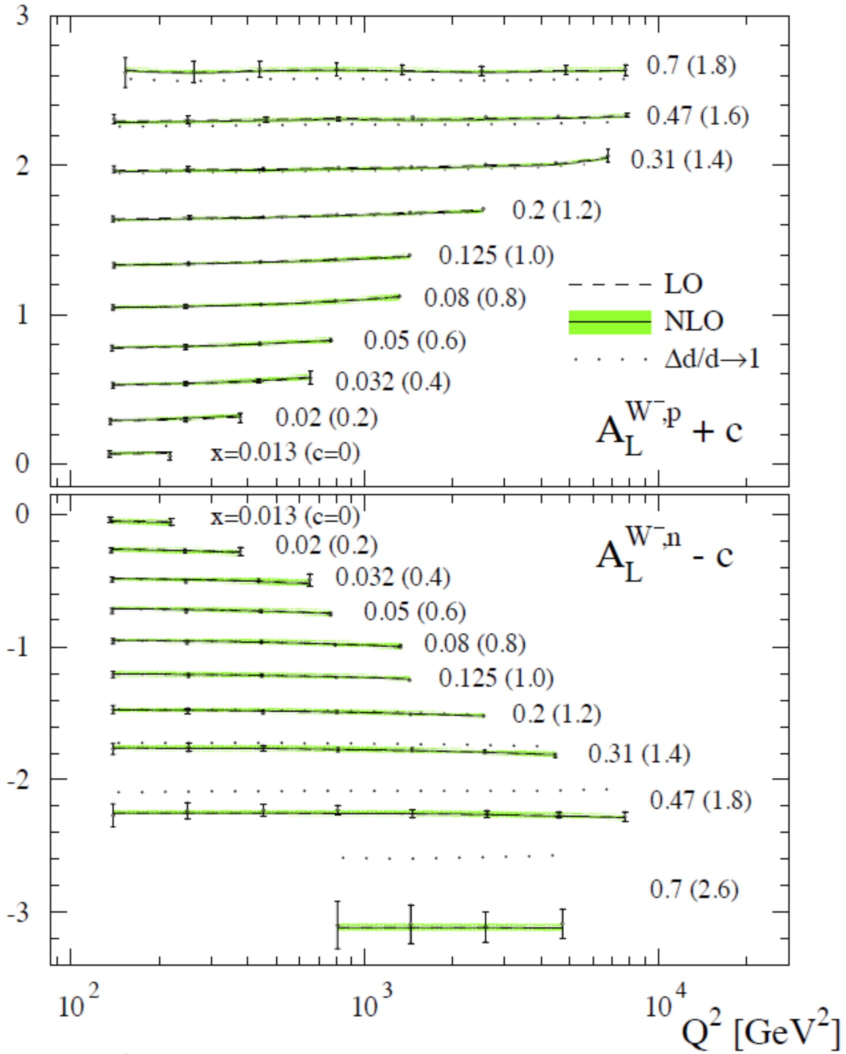
- Constraints on gluon and quark contributions will provide independent check of orbital angular momentum component of proton spin

RHIC: Probing the Sea

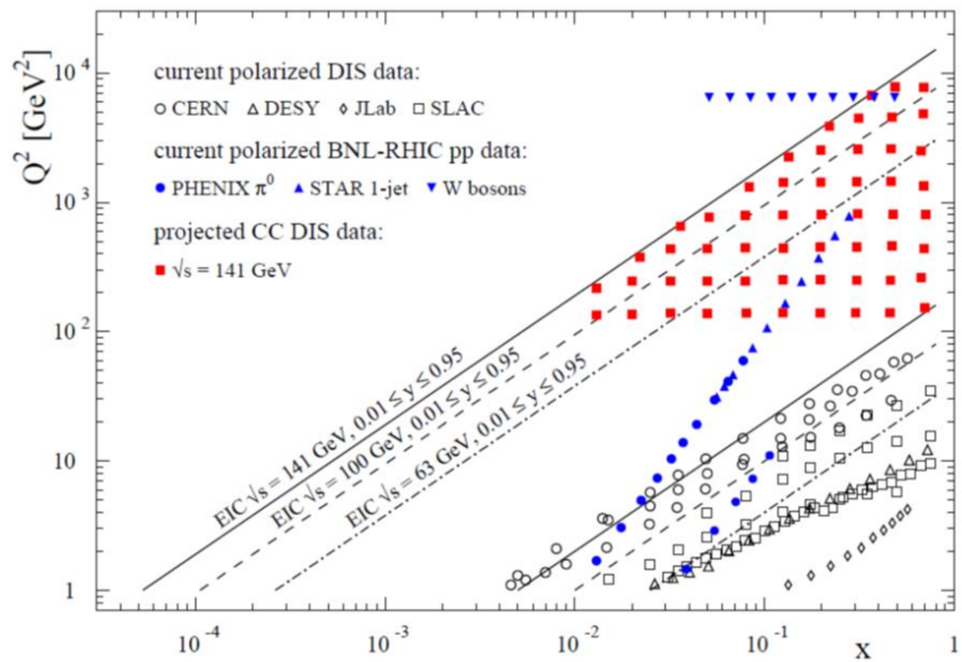


Nucl. Phys. B 887, 276 (2014)

eRHIC: Probing the Sea

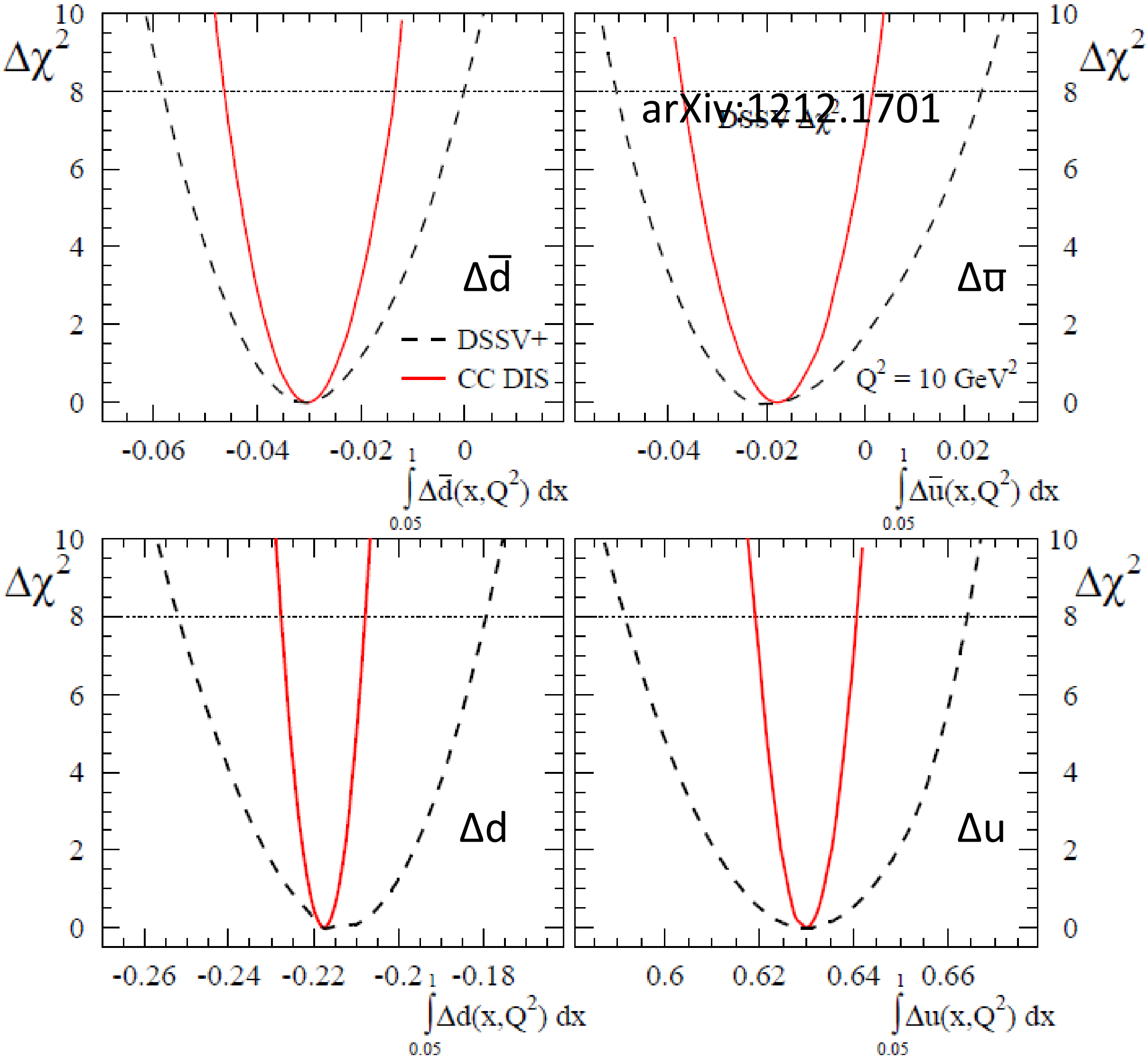


arXiv:1409.1633



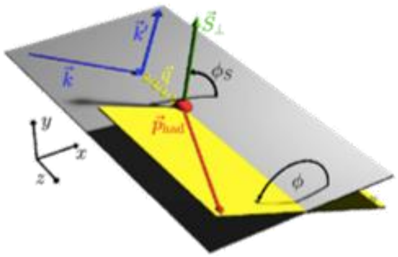
- DIS largely 1-photon exchange, but can also proceed via charged current (CC) interaction mediated by W boson
- CC interactions in polarized DIS give access to quark / antiquark helicity distributions as well as unique structure functions
- Because W is virtual, can access lower values of Q^2 to overlap with and provide cross check to SIDIS measurements

eRHIC: Quark / Anti-Quark Constraints



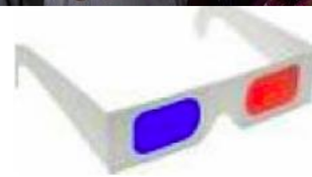
- eRHIC with 5 GeV electrons colliding with 100 and 250 GeV protons greatly reduce uncertainty on u and d anti-quark helicity distributions
- See significant reduction in uncertainty on first moment of quark/anti-quark helicity distributions for x > 0.05 from 20 x 250 GeV electron on proton collisions

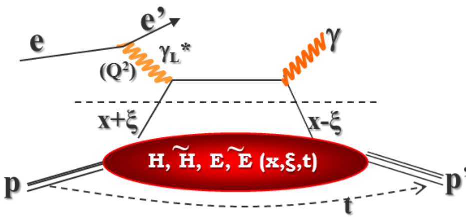
Quantum Tomography of the Nucleons



TMDs

GPDs





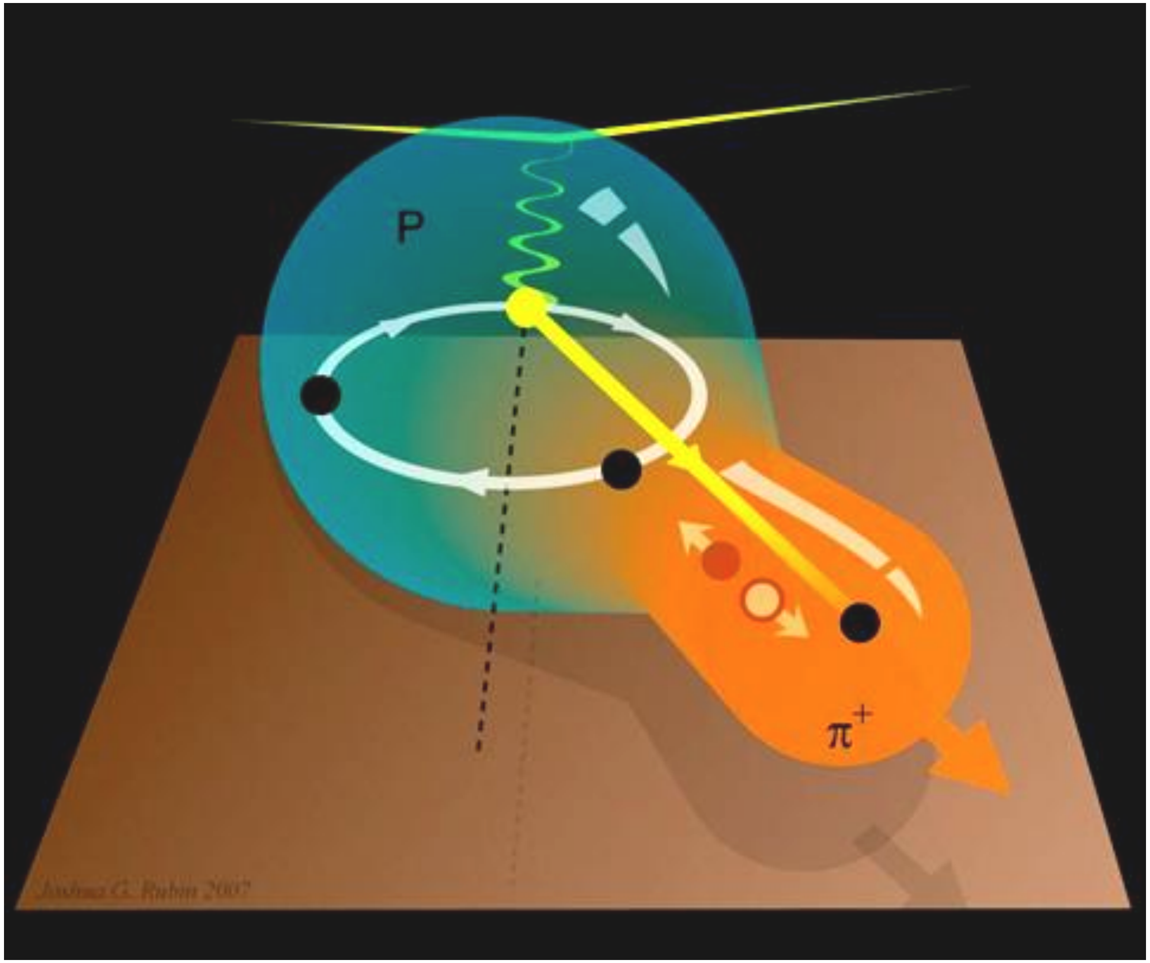
2D+1 picture in momentum space

2D+1 picture in coordinate space

Spin as vehicle to do tomography of the nucleon

- What is the dynamic structure of the proton and nuclei
- 2D+1 picture in momentum and coordinate space
- Visualize color interactions in QCD
- Collective phenomena and correlations in fragmentation
- New physics aspects due to confined motion

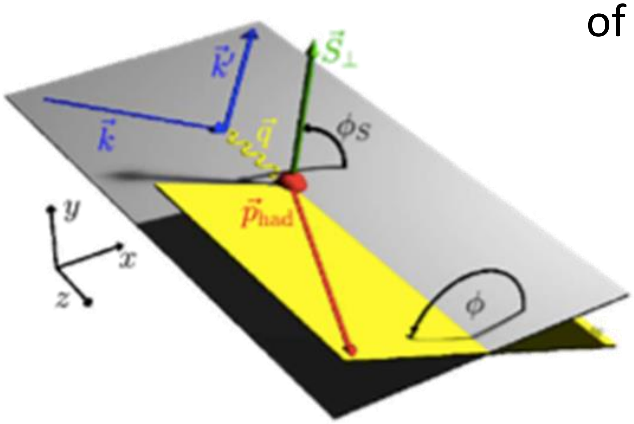
TMDs



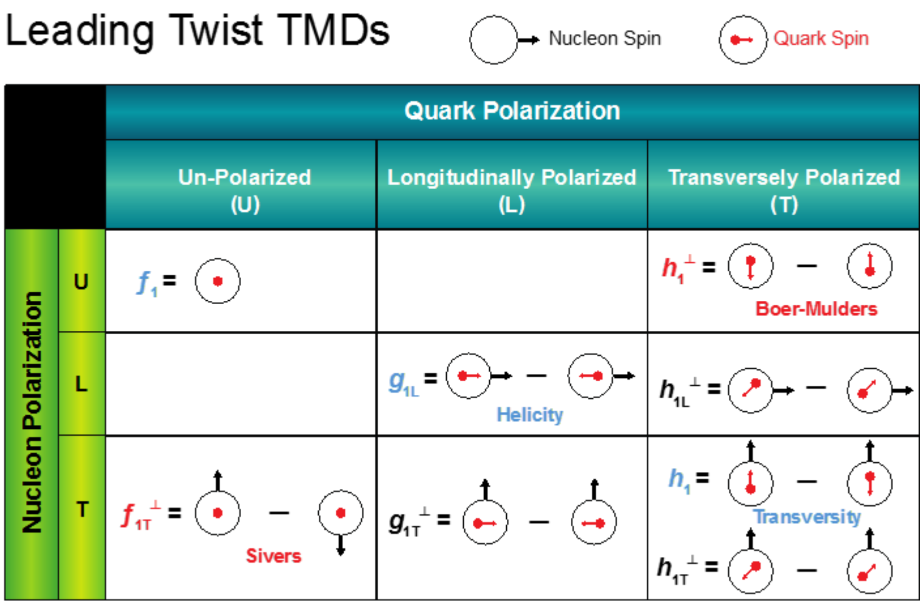
TMDs

Observable: azimuthal modulations of 6-fold differential SIDIS cross section

$$\frac{d\sigma}{dx\,dQ^2\,dz\,d\phi_s\,d\phi_h\,dp_T^h}$$



- Theoretically interesting multi-scale problem: Q^2, p_T
- TMD framework/factorization applicable for $Q^2 >> p_T$
- So far if at all only valence quark TMDs extracted from fixed target data
- Very different evolution then collinear PDFs perturbative & non-perturbative contributions
- Slew of different TMDs can be defined

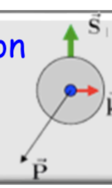


Similar for gluons

Example

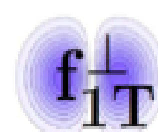
Sivers function

$\sin(\phi_h - \phi_s)$ modulation



correlation of nucleon's transverse spin with the k_T of an unpolarized quark

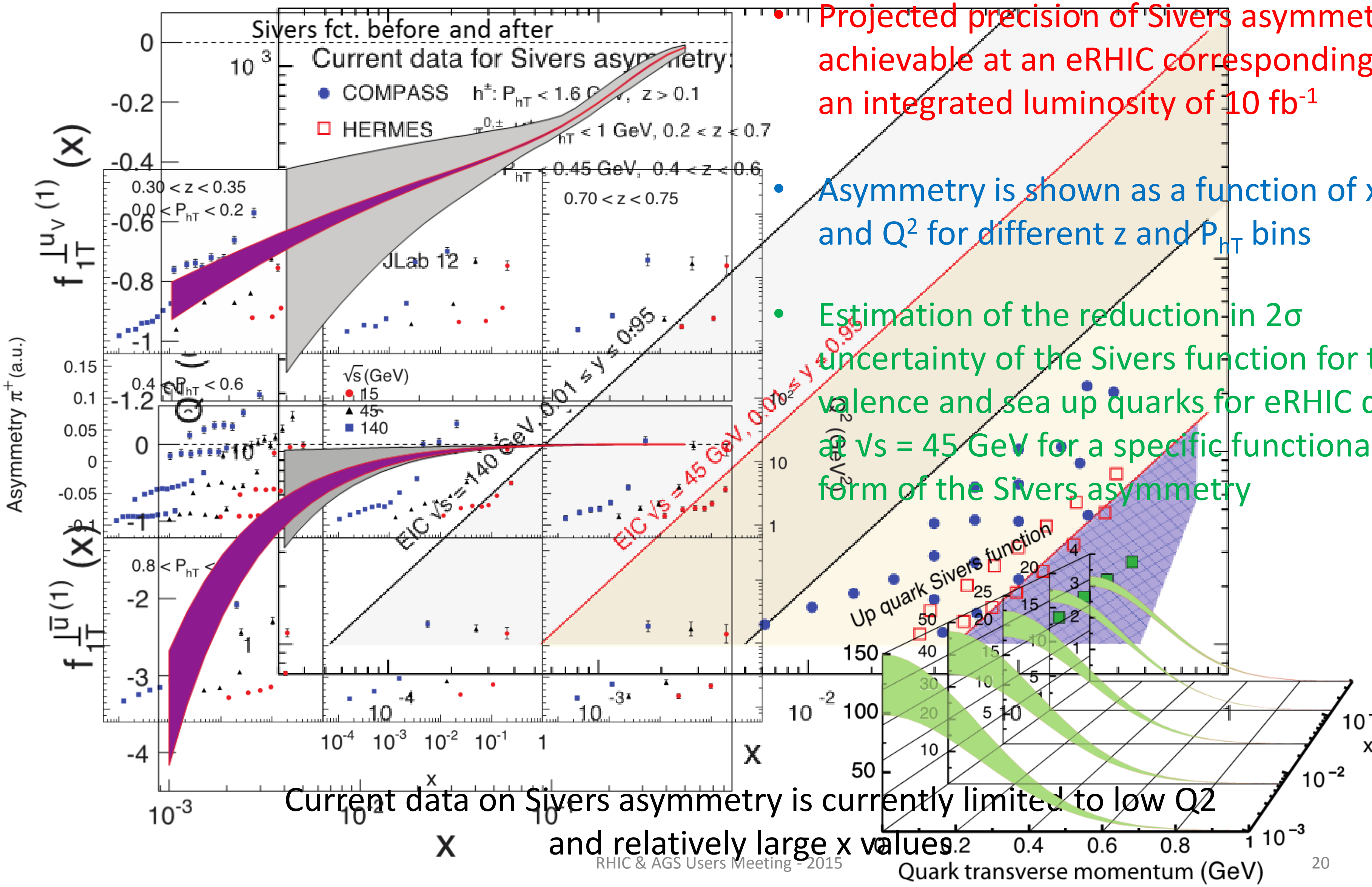
$$f_{q/P^\uparrow}(x, \mathbf{k}_\perp, S) = f_1(x, \mathbf{k}_\perp^2) - \frac{\mathbf{S}\cdot(\hat{\mathbf{P}}\times\mathbf{k}_\perp)}{M} f_{1T}^\perp(x, \mathbf{k}_\perp^2)$$



Sivers function

- measures spin-orbit correlations
- link to parton orbital motion (through models)
- reveals non-trivial aspects of QCD color gauge invariance

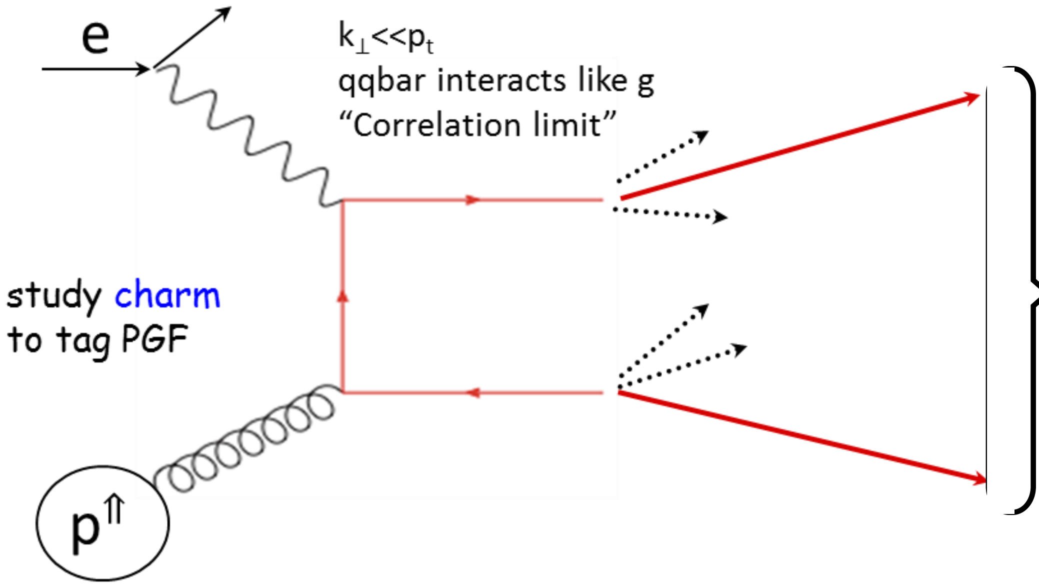
TMDs: Before and After eRHIC



- Projected precision of Sivers asymmetries achievable at an eRHIC corresponding to an integrated luminosity of 10 fb^{-1}
- Asymmetry is shown as a function of x and Q^2 for different z and P_{hT} bins
- Estimation of the reduction in 2σ uncertainty of the Sivers function for the valence and sea up quarks for eRHIC data at √s = 45 GeV for a specific functional form of the Sivers asymmetry

Current data on Sivers asymmetry is currently limited to low Q2 and relatively large x values

Accessing The Gluon Sivers Function



Measure a pair of D mesons

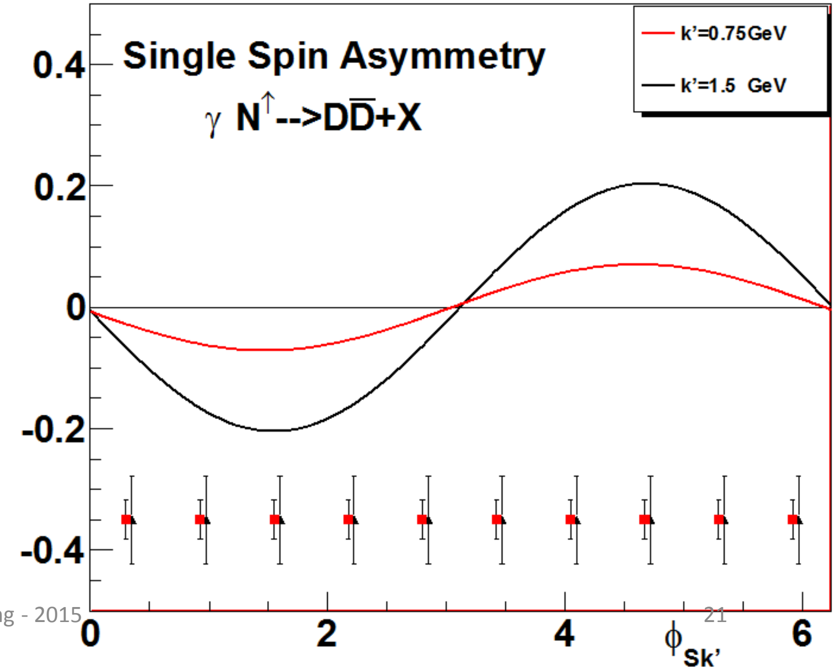
Statistically challenging

$k_\perp = |k_{1T} + k_{2T}|$

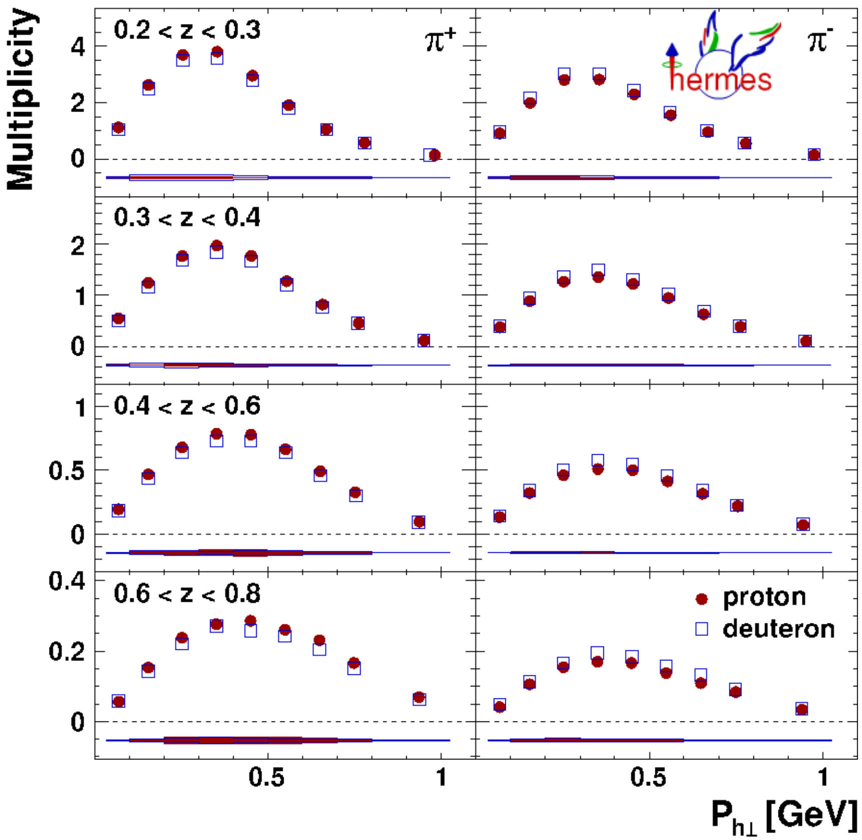
$P_T = (k_{1T} - k_{2T}) / 2$

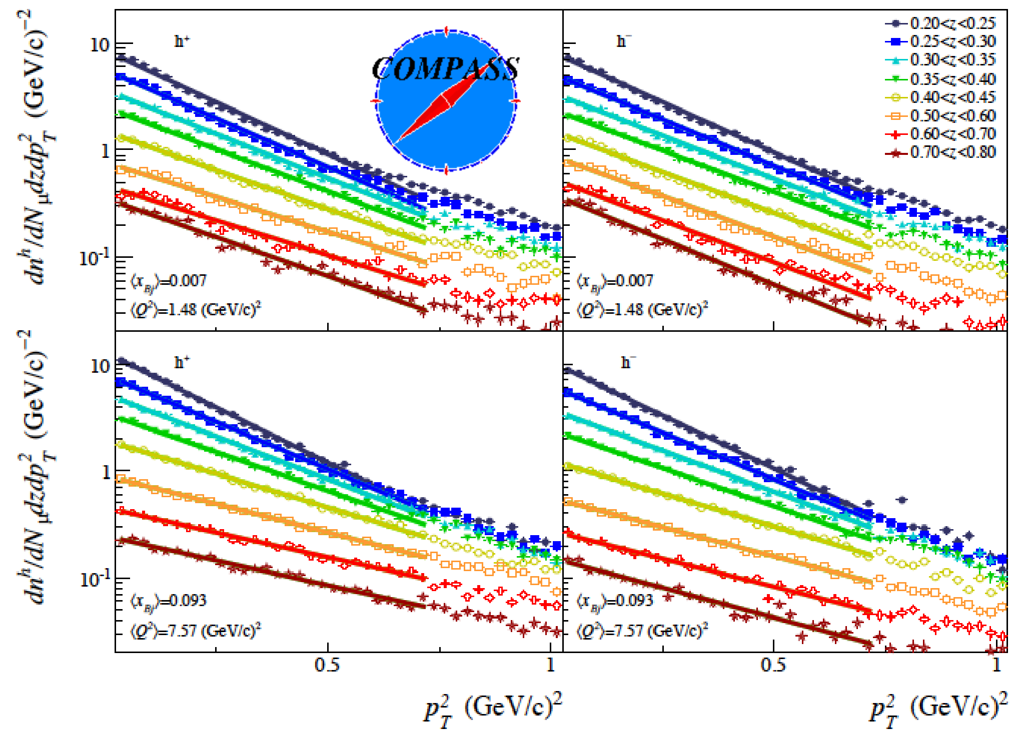
$$A(k'_\perp, \phi_{Sk'}) = \frac{d\sigma(k'_\perp, \phi_{Sk'}) - d\sigma(k'_\perp, \phi_{Sk'} + \pi)}{d\sigma(k'_\perp, \phi_{Sk'}) + d\sigma(k'_\perp, \phi_{Sk'} + \pi)}$$

- Beam Energies: 20 GeV x 250 GeV
- Q^2: 1 – 10 GeV^2, y: 0.01 – 0.95, z>0.25
- No cut on $k_\perp$ and p_t, but on $k_\perp/p_t < 0.5$ for "correlation limit"
- Statistical precision corresponds to roughly 8 months of running (50% efficiency) at L = 10^{34} $cm^2 s^{-1}$



Parameterizing Primordial k_T

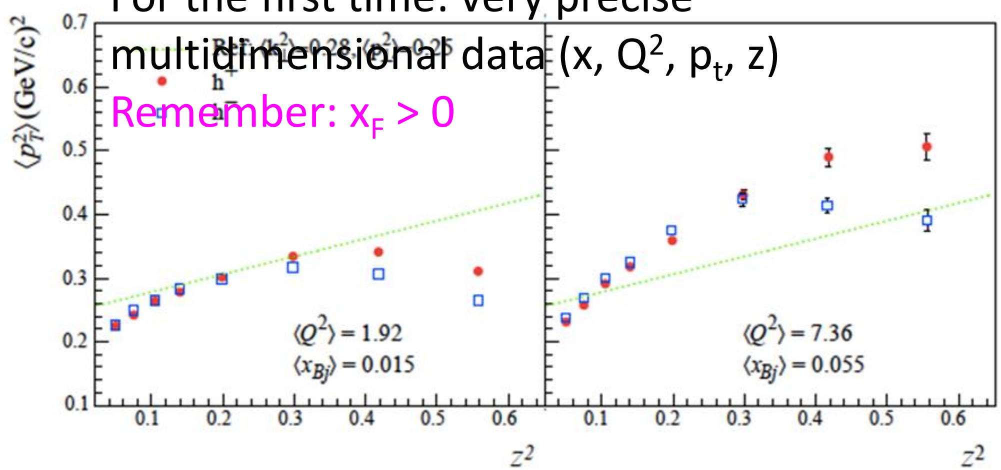




Fit: $\left\langle p_t^2 \right\rangle_q = \left\langle p_\perp^2 \right\rangle_q + z^2 \left\langle k_\perp^2 \right\rangle_q$

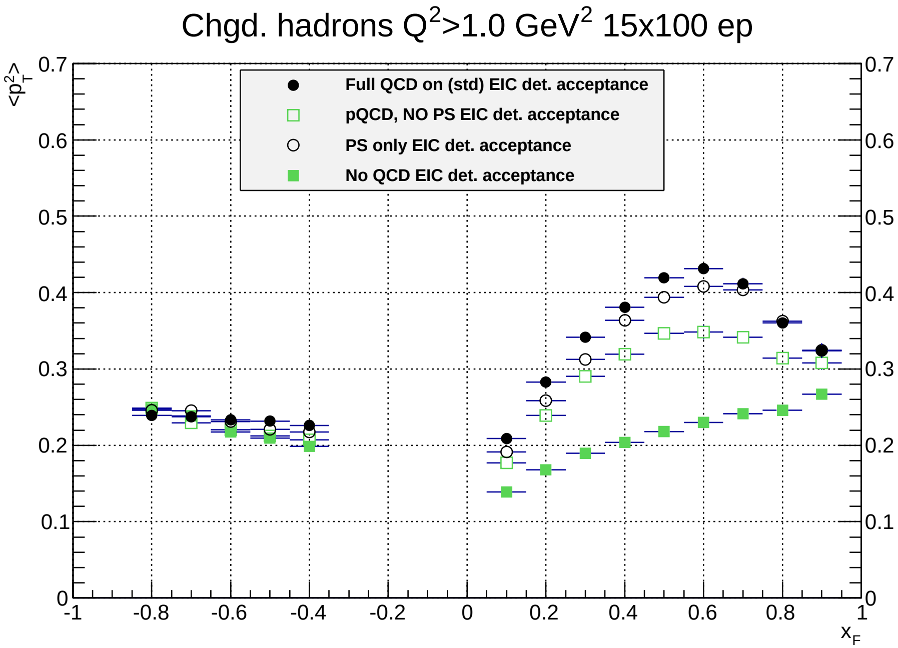
For the first time: very precise multidimensional data (x, Q^2, p_t, z)

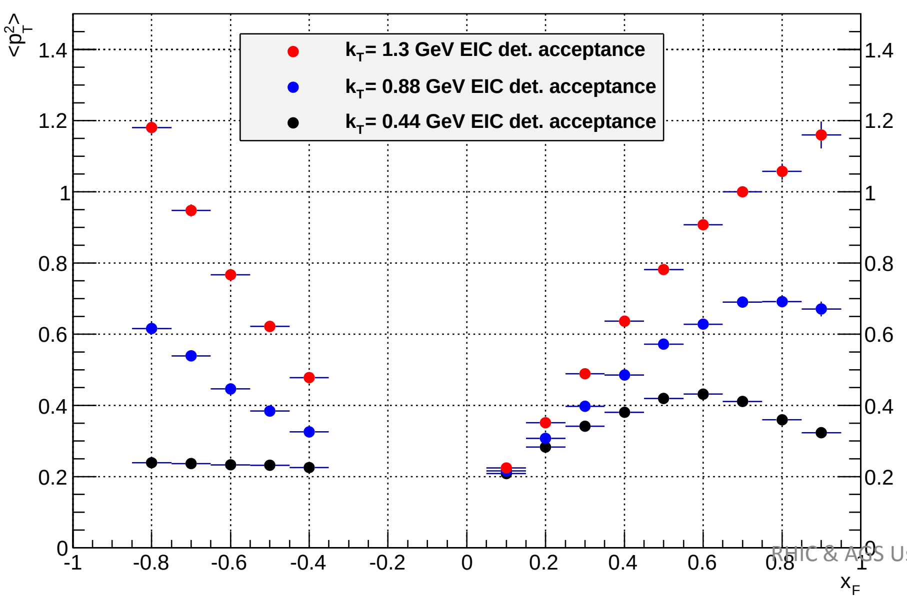
Remember: $x_F > 0$



- TMD inspired fit is not a good representation
- Need to account for different underlying sub-processes
- Neglects other dependences

Accessing Primordial k_T



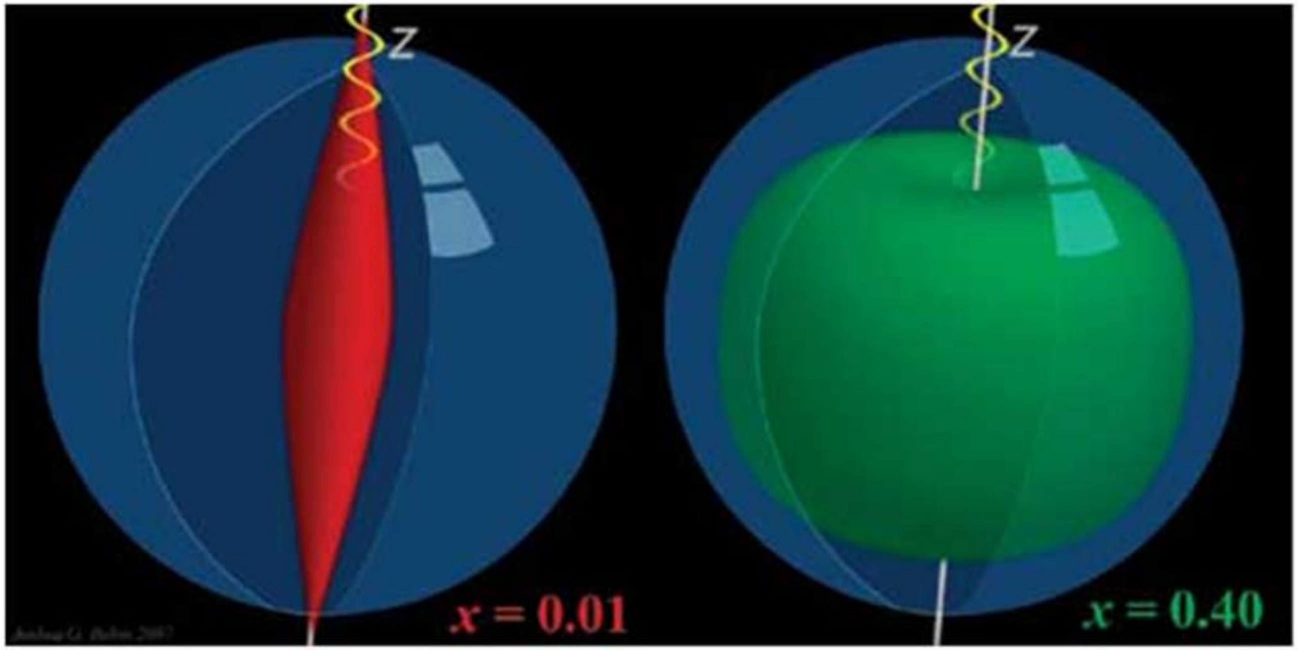


4 different contributions to the p_t of a hadron

- k_t: non-perturbative; very often called "intrinsic"
- k_t^{PS}: from parton showers → connection to soft factors in TMDs
- p_t^{frag}: p_t contribution from the fragmentation
- p_t^{hard} : from hard QCD scattering (QCDC, PGF, …)

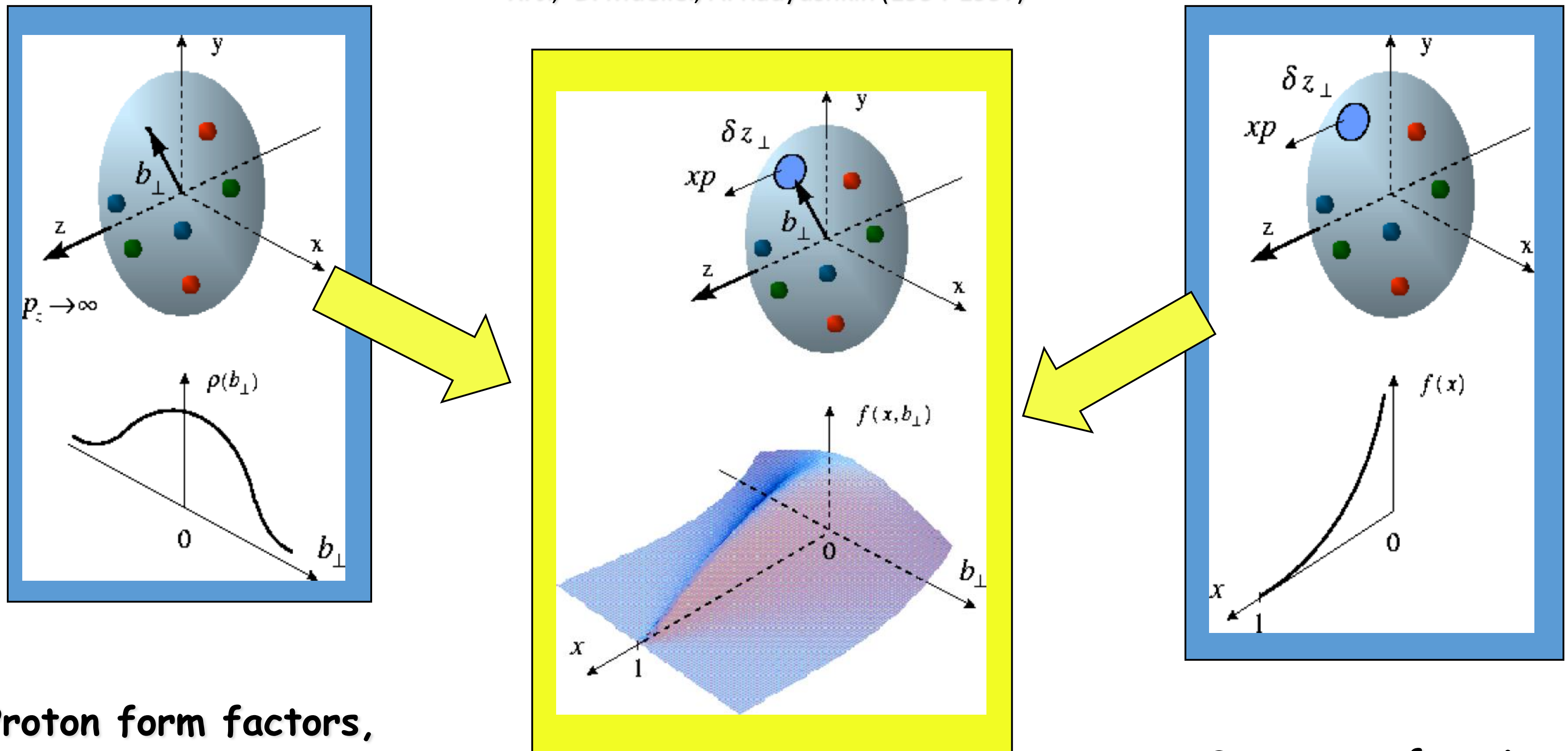
- x_F>0: "struck" parton hemisphere
- x_F<0 "target remnant" hemisphere sensitive to intrinsic k_t
- What else can be learned from x_F<0 region?

Generalized Parton Distributions



Beyond Form Factors and PDFs

X. Ji, D. Mueller, A. Radyushkin (1994-1997)



Proton form factors, transverse charge & current densities

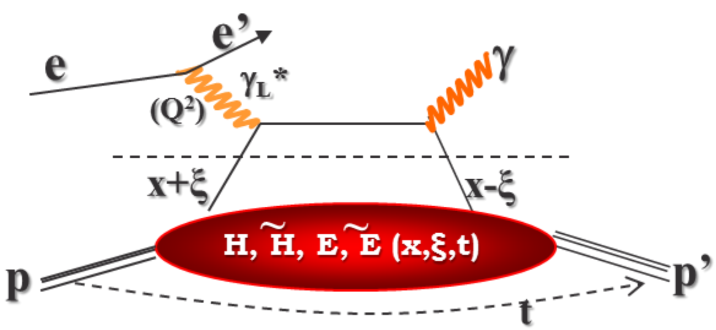
Correlated quark momentum and helicity distributions in transverse space - GPDs

Structure functions, quark longitudinal momentum & helicity distributions

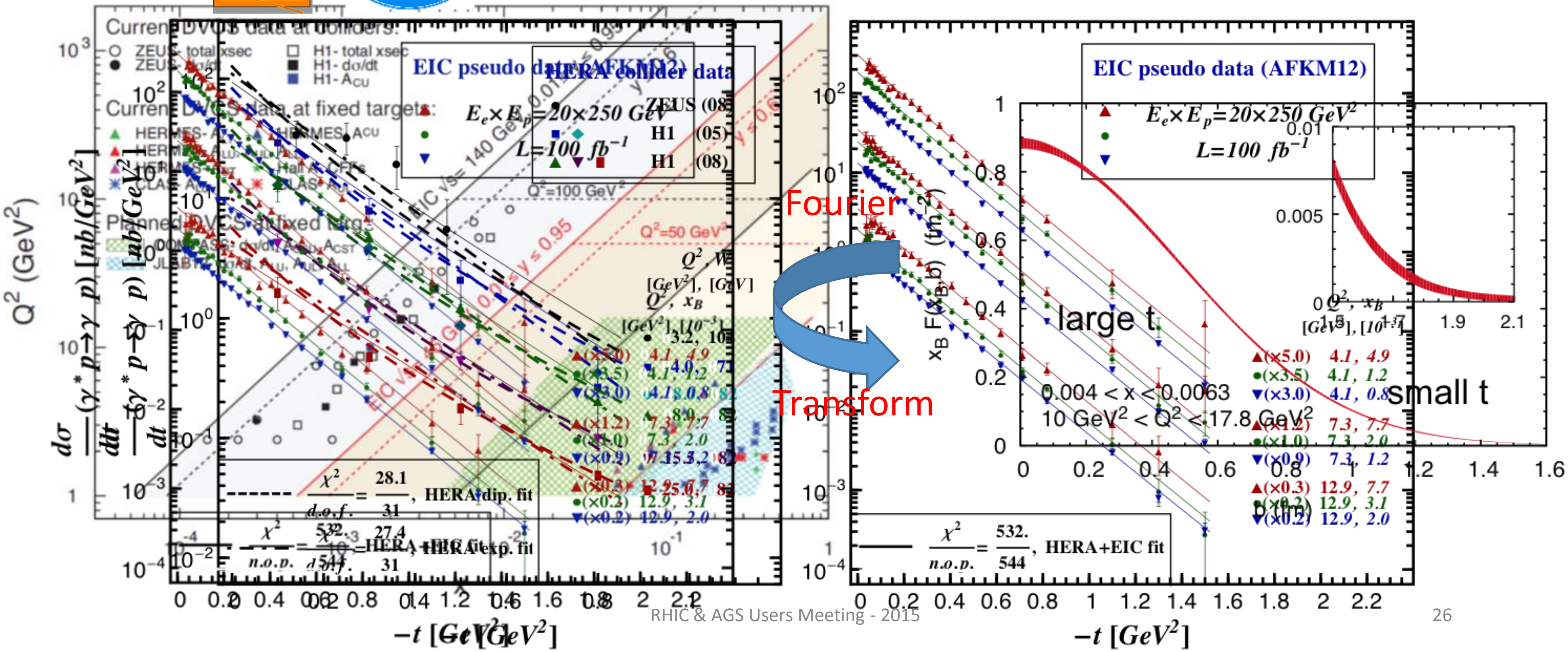
the way to 3d imaging of the proton and the orbital angular momentum L_q & L_g

Constrained through exclusive reactions

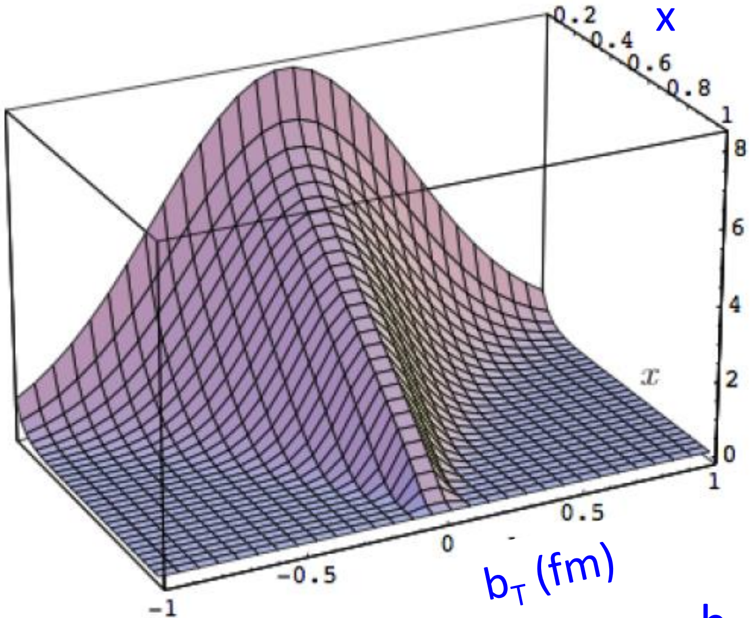
GPDs: Kinematic Coverage

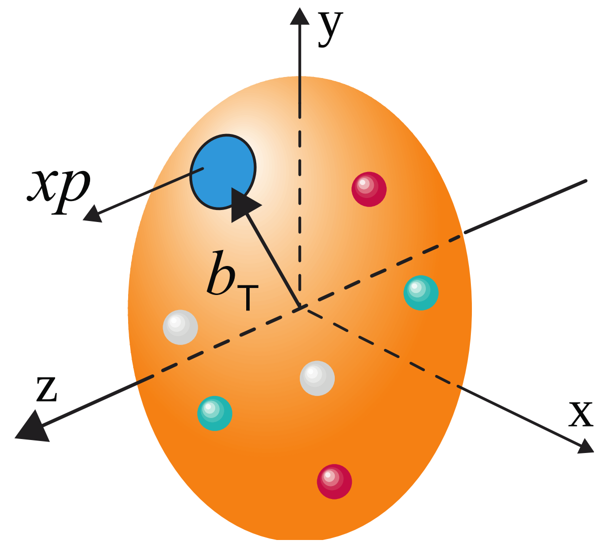


- Kinematic coverage of existing DVCS data and eRHIC range
- H1 and ZEUS DVCS cross sections and projected eRHIC statistical precision
- Fourier transform gives impact parameter dependence

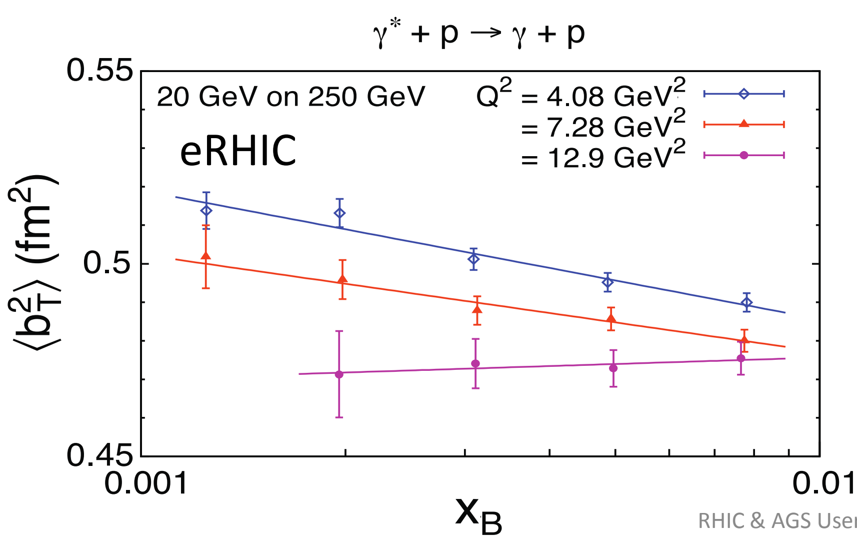


Model of a Quark GPD





b_T decreasing as a function of x

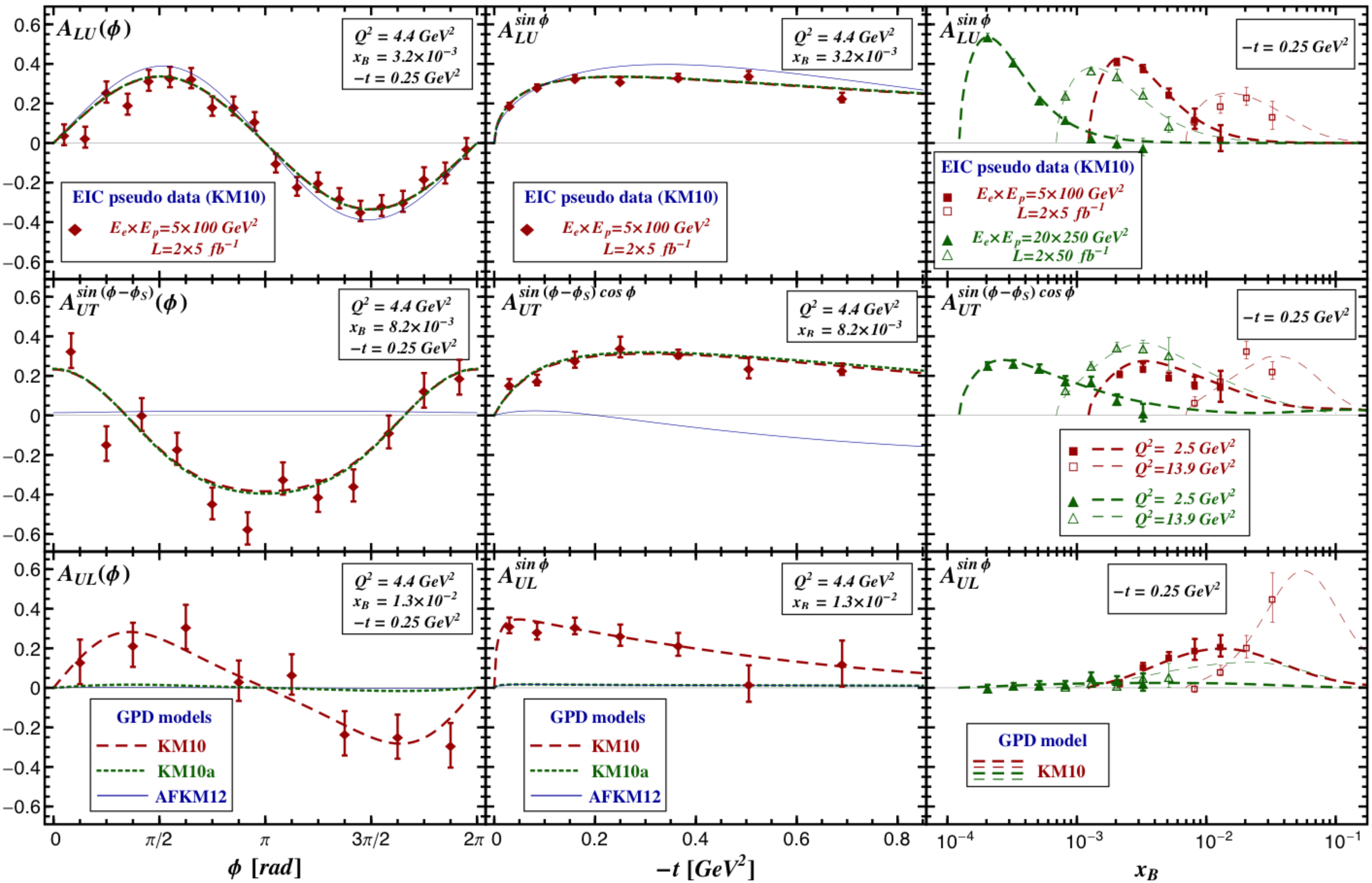


Valence (high x) quarks at the **center** → small b_T

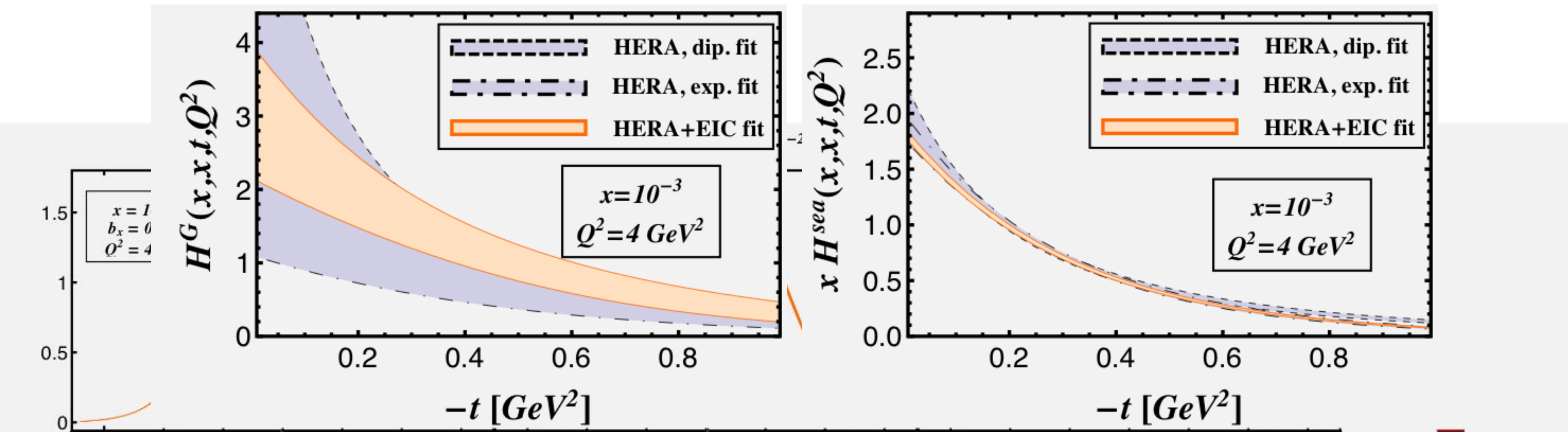
Sea (small x) quarks at the **periphery** → high b_T

GLUONS ???

DVCS Asymmetries



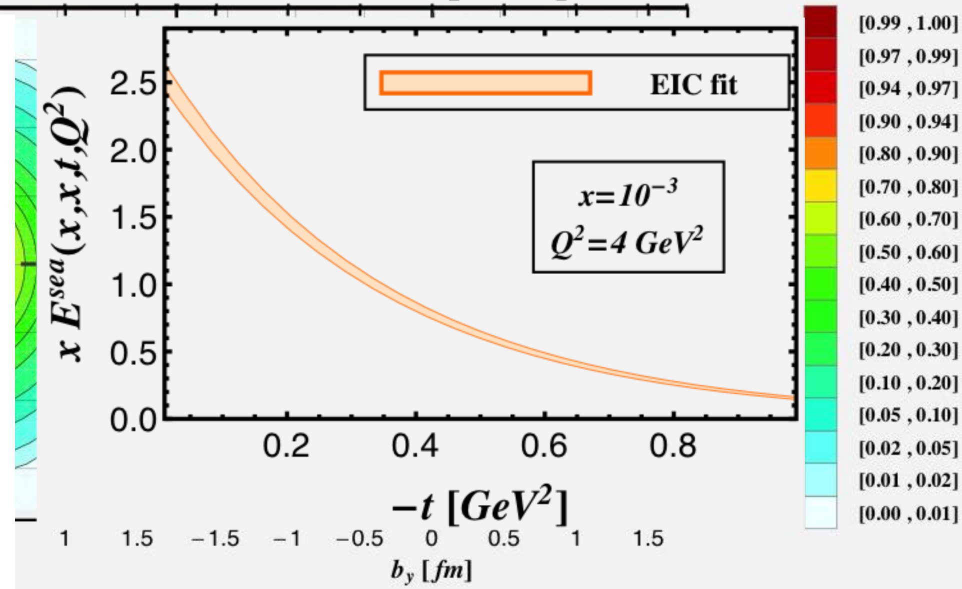
2D+1 Structure of the Nucleon



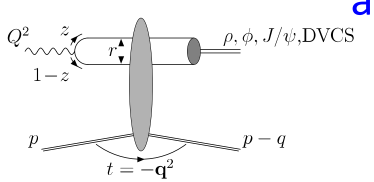
- **A global fit over all** pseudo **data was done, based on the GPDs-based model: [K. Kumerički, D Müller, K. Passek-Kumerički 2007]**

- **Known values *q(x), g(x)* are assumed for H^q, H^g (at x=0, t=0 forward limits E^q, E^g are unknown)**

- **Excellent reconstruction of H^{sea}, E^{sea} and good reconstruction of H^g (from *dσ/dt*)**

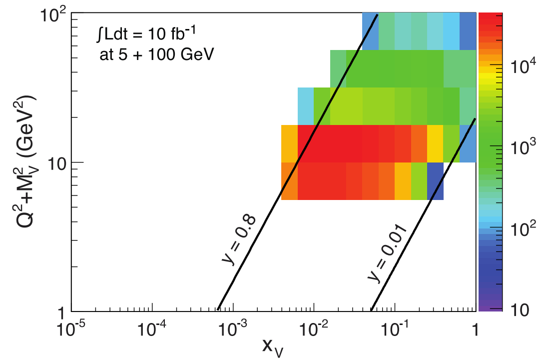


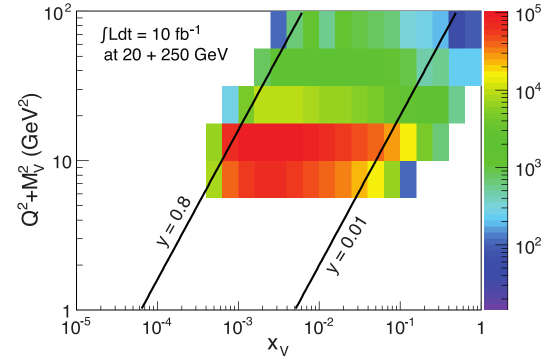
GPD H^g: J/Ψ

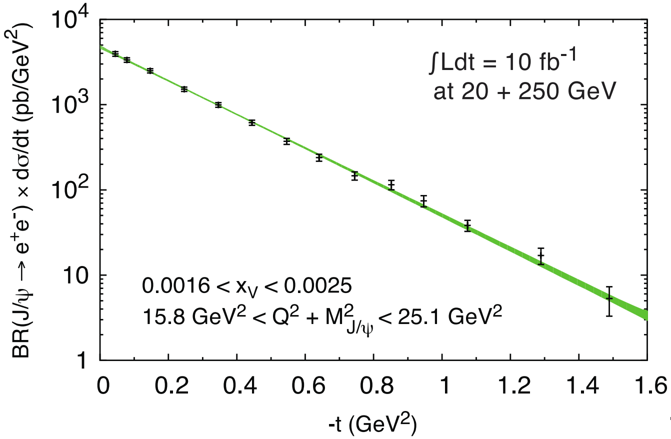


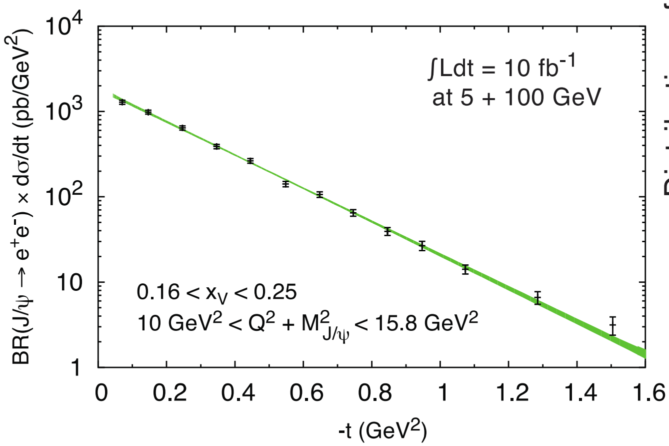
To improve imaging on gluons
add J/ψ observables

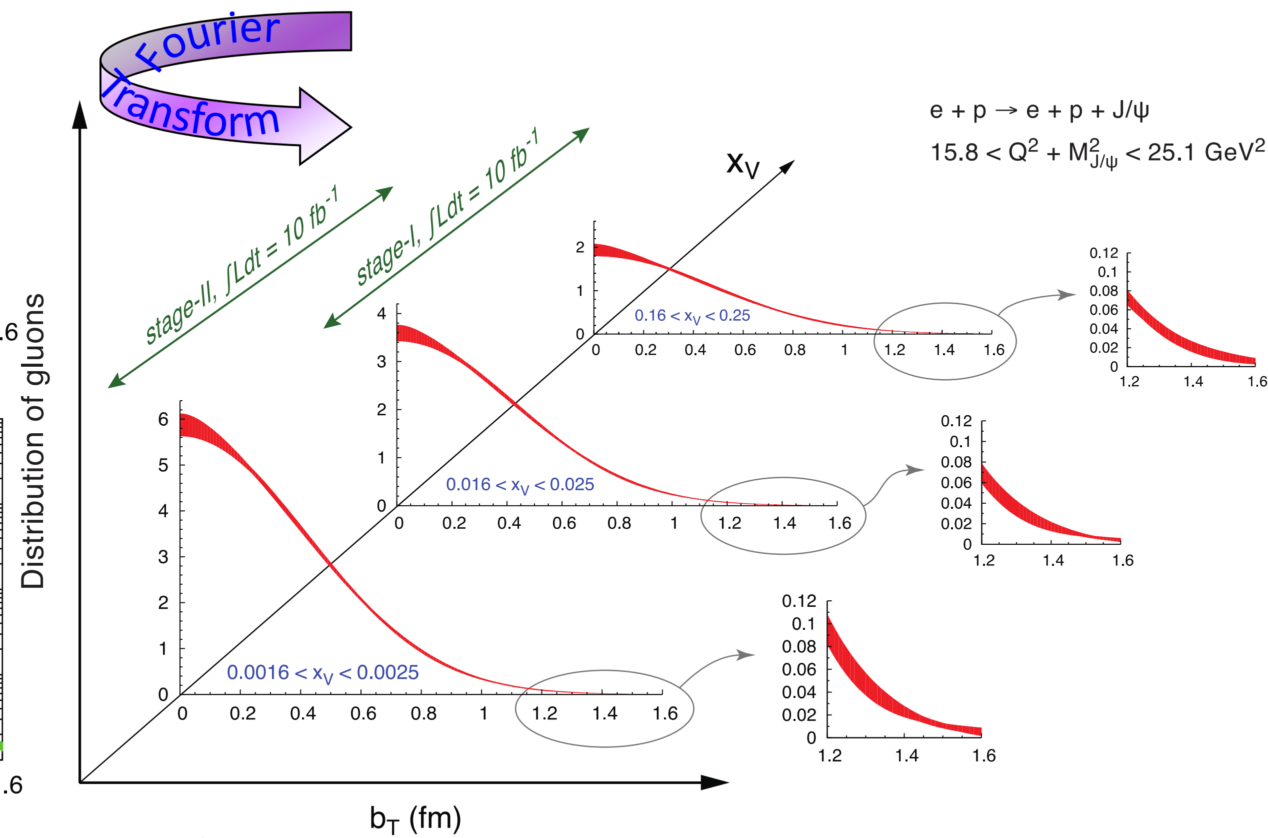
- ❑ cross section
- ❑ A_{UT}
- ❑ .....











Summary

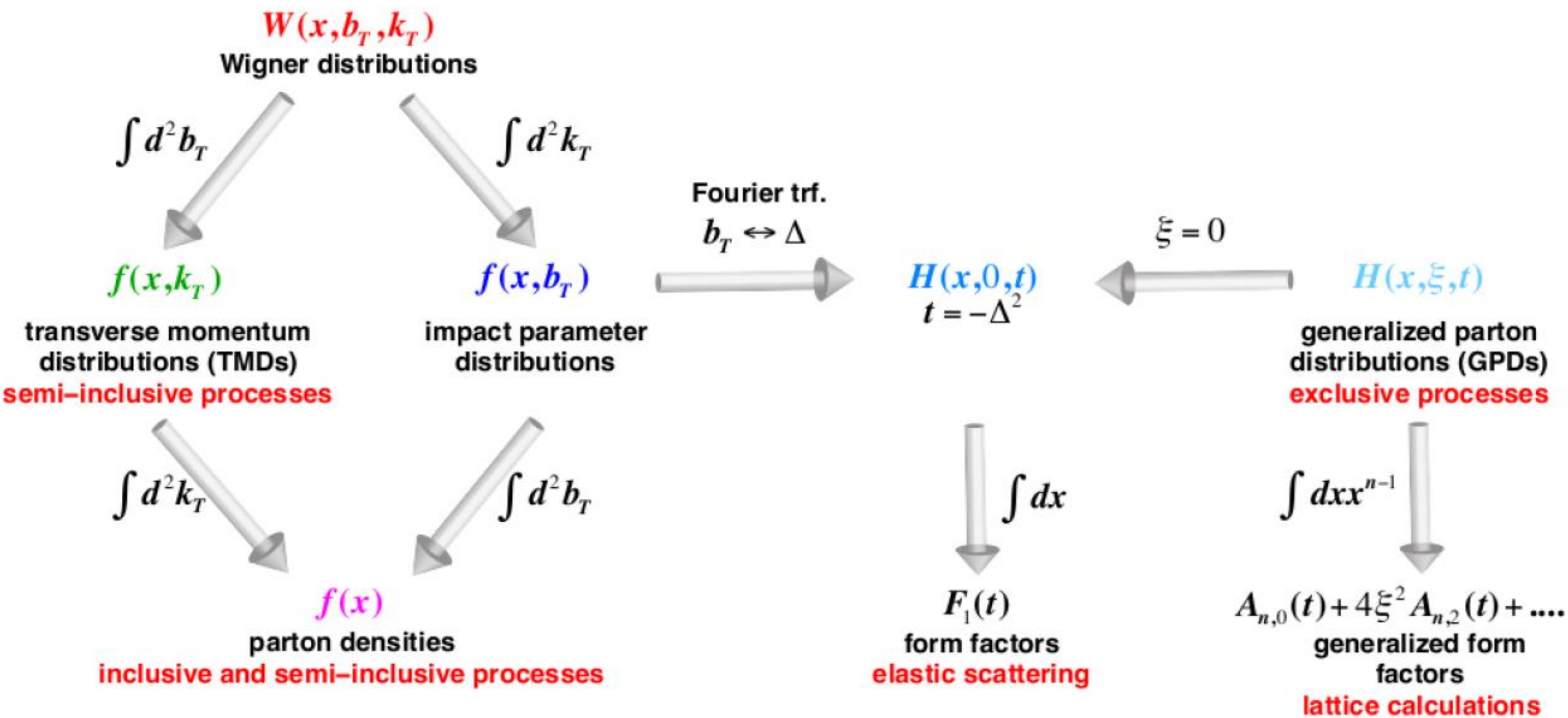
- Adding a polarized electron beam to RHIC will combine the large kinematic reach of colliders, the precision of leptonic probes, and full polarization control to produce the ultimate laboratory for the exploration of QCD

- Precision measurements of the $g_1(x,Q^2)$ structure function, along with SIDIS and charged current probes will pin down the helicity structure of the proton

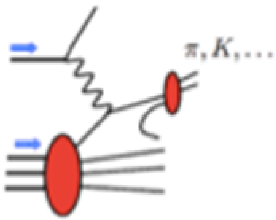
- Access to TMDs and GPDs will give full 2D+1 structure of the proton in transverse momentum and impact parameter space and probe the orbital angular momentum component of the proton spin

- In addition to polarized e+p, a rich physics program utilizing heavy nuclei will be possible

PDF Family Tree



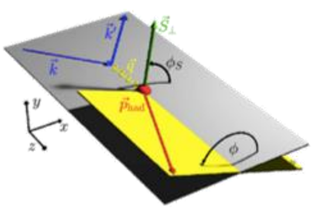
Golden Probes and Requirements



Spin and flavor structure of the nucleon			
Deliverables	Observables	What we learn	Requirements
polarized gluon distribution Δg	scaling violations in inclusive DIS	gluon contribution to proton spin	coverage down to $x \simeq 10^{-4}$; $\mathcal{L}$ of about 10 fb^{-1}
polarized quark and antiquark densities	semi-incl. DIS for pions and kaons	quark contr. to proton sp asym. like $\Delta\bar{u} - \Delta\bar{d}$; Δ	
novel electroweak spin structure functions	inclusive DIS at high Q^2	flavor separation at medium x and large Q^2	$\sqrt{s} \geq 100$ GeV; $\mathcal{L} \geq 10$ fb^{-1} positrons; polarized ^{3}He beam

$\int Ldt = 10$ fb^{-1}

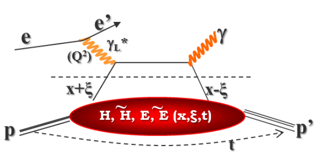
All measurements need $\sqrt{s_{ep}} > 50$ GeV to reach $x < 10^{-3}$ where sea quarks and gluons dominate



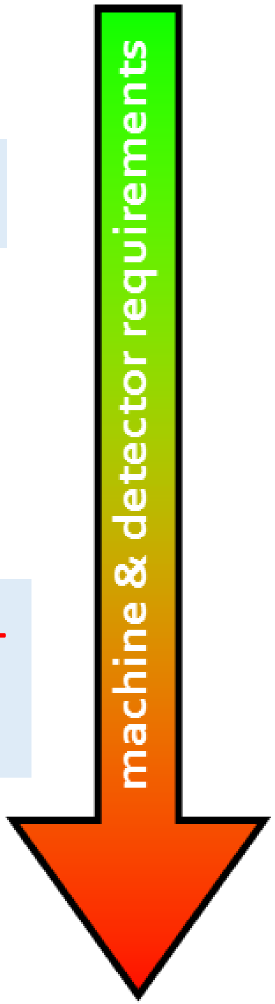
uclei: transverse momentum dependence		
earn	Phase I	Phase II
ference n and it ns	valence+sea quarks, overlap with fixed target	3D Imaging of quarks and gluon; Q^2 ($P_\perp$) range

$\int Ldt = 10$ fb^{-1} -

$\int Ldt = 100$ fb^{-1}



Three-dimensional structure of the nucleon and nu			
Deliverables	Observables	What we learn	
sea quark and gluon GPDs	DVCS and $J/\psi, \rho, \phi$ production cross sect. and asymmetries	transverse images of sea quarks and gluons in nucleon and nuclei; total angular momentum; onset of saturation	$\mathcal{L} \geq 10^{34}$ cm^{-2}s^{-1}, Roman Pots wide range of x_B and Q^2 polarized e^- and p beams e^+ beam for DVCS



Golden Measurements

Spin and flavor structure of the nucleon			
Deliverables	Observables	What we learn	Requirements
polarized gluon distribution Δg	scaling violations in inclusive DIS	gluon contribution to proton spin	coverage down to $x \simeq 10^{-4}$; $\mathcal{L}$ of about 10 fb^{-1}
polarized quark and antiquark densities	semi-incl. DIS for pions and kaons	quark contr. to proton spin; asym. like $\Delta\bar{u} - \Delta\bar{d}$; Δs	similar to DIS; good particle ID
novel electroweak spin structure functions	inclusive DIS at high Q^2	flavor separation at medium x and large Q^2	$\sqrt{s} \geq 100$ GeV; $\mathcal{L} \geq 10$ fb^{-1} positrons; polarized ^{3}He beam

Three-dimensional structure of the nucleon and nuclei: transverse momentum dependence				
Deliverables	Observables	What we learn	Phase I	Phase II
Sivers and unpolarized TMDs for quarks and gluon	SIDIS with transv. polarization/ions; di-hadron (di-jet) heavy flavors	quantum interference multi-parton and spin-orbit correlations	valence+sea quarks, overlap with fixed target experiments	3D Imaging of quarks and gluon; Q^2 ($P_\perp$) range QCD dynamics

Three-dimensional structure of the nucleon and nuclei: spatial imaging			
Deliverables	Observables	What we learn	Requirements
sea quark and gluon GPDs	DVCS and $J/\psi, \rho, \phi$ production cross sect. and asymmetries	transverse images of sea quarks and gluons in nucleon and nuclei; total angular momentum; onset of saturation	$\mathcal{L} \geq 10^{34}$ cm^{-2}s^{-1}, Roman Pots wide range of x_B and Q^2 polarized e^- and p beams e^+ beam for DVCS

QCD matter in nuclei				
Deliverables	Observables	What we learn	Phase I	Phase II
integrated gluon distributions	$F_{2,L}$	nuclear wave function; saturation, Q_s	gluons at $10^{-3} \leq x \leq 1$	explore sat. regime
k_T-dep. gluons; gluon correlations	di-hadron correlations	non-linear QCD evolution/universality	onset of saturation; Q_s	RG evolution
transp. coefficients in cold matter	large-x SIDIS; jets	parton energy loss, shower evolution; energy loss mech.	light flavors, charm bottom; jets	precision rare probes; large-x gluons

Electroweak interactions and physics beyond the Standard Model				
Deliverables	Observables	What we learn	Phase I	Phase II
Weak mixing angle	Parity violating asymmetries in ep- and ed-DIS	physics behind electroweak symmetry breaking and BSM physics	good precision over limited range of scales	high precision over wide range of scales
e-τ conversion	$ep \to \tau, X$	flavour violation induced by BSM physics	challenging	very promising